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Evolution in Military Affairs:

The Chaotic Development of Infrared Systems For Tactical Aviation

by

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Preface

I must acknowledge up front that I have made many generalizations and oversimplifications throughout this paper. I have tried to cover two complex technologies over a 50 year time period through several military conflicts while trying to draw analogs to chaotic and evolutionary development methods that are the latest fad in the business world. Clearly, some details will be slighted or glossed over. Also, because I have had a small role (very small) in some of the developments covered in the paper, I occasionally rely on personal experience and observations to fill in details. Clearly that leaves ample room for bias and distortion on my part. Nevertheless, I believe the general trends discussed in this paper are valid and can withstand scrutiny, even if some details can be haggled over. In any case, if all the paper accomplishes is introducing the concept and highlighting the potential of chaotic evolutionary development as a model for future military system development, then the paper will have served its primary purpose.

I must acknowledge the advisors in the Center for Strategy and Technology, Dr Hammond and Col (R) Hailes for allowing me the time and opportunity to "think big thoughts" in the midst of the minutiae of everyday student life at Air War College. I would also like to acknowledge Lt Col Beth Kaspar who recommended the book "Competing on the Edge of Chaos." I hated the book, the *first* time I read it, but it eventually became the inspiration for this paper. Lt Col John Brunderman should also get some credit for forcing me to defend natural evolution on numerous occasions.

Abstract

The concept of using natural evolution as an analogy for how modern organizations can adapt to a chaotic, rapidly changing world situation is currently in vogue in the business world. This paper will examine whether the chaotic evolutionary development model is pertinent to the US military's attempt to adapt to the uncertain national security environment of the post Cold War world. The paper will look at the historical example of the development of infrared (IR) systems for tactical aviation in order to see how the natural evolution model can be applied to the development of military systems. The evolutionary development of IR systems will be "benchmarked" against the more traditional planned development of radar systems. The theme of the paper is that the chaotic evolutionary development of IR systems has been successful and has had a significant effect on the current state of air operations. The general conclusion of the paper is that the natural evolution development model has many analogies to the way IR systems were developed and employed and contains many useful insights to consider for future development. Understanding this analogy and its limits may hold the key for developing a more flexible development system that will be better able to adapt to the uncertain security environment of the future. In the epilogue, the paper will address how such evolutionary development might be applied to the attempt to plan an information-based Revolution in Military Affairs.

Introduction

Falcon lead and his wingman, a flight of two Joint Strike Fighters, cruised above a thin cloud layer in the clear night sky. JSTARS had vectored them to an area that had just been struck by a barrage of sensor-fuzed weapons so they could mop up the survivors of a shattered enemy armored column. Falcon flight was relatively safe above the cloud layer since the enemy had learned long ago that the USAF combination of stealthy platforms, electronic countermeasures, and SEAD made it dangerous to emit for even a few seconds.[1] With the enemy denied the use of active radar, the JSF flight was undetected above the clouds. Falcon lead knew that using his own radar was also risky since the enemy had learned to listen to, rather than emit, radar signals. Passive detection systems could cue AAA barrage fire or ballistic SAM launches which might only use radar for a few seconds for terminal guidance. Fortunately, his multi-spectral infrared (IR) system meant he could remain silent, as well as unseen. The IR system had been slaved to his wingman's position to monitor formation integrity for the enroute portion of the flight. Now, as he approached the GPS coordinates of the target area, he slewed the IR forward and manually switched to millimeter wave frequency to look through the clouds for the "cold spots" signifying metal objects. After scanning the area, the sensor switched automatically to hyperspectral mode and scanned each metal target, comparing their signatures to its stored target library and storing the position of those objects most likely to be enemy tanks. As the flight dipped below the cloud layer for its attack run, the sensor switched to thermal mode to increase resolution and to see which targets were "hot." The smoke from the previous strike and the sparse tree cover had little effect on the IR image. The pilot opened the weapons bays and caged the infrared seeker heads of the four hypervelocity missiles stored in his JSF. After ripple firing the missiles and visually confirming that his wingman had done the same, Falcon lead turned and climbed back into the relative safety above the cloud deck, leaving his fire-and-forget missiles to finish the strike on their own.

Falcon flight was able to accomplish a difficult mission, striking dispersed armor at night, below the weather on a smoky battlefield filled with non-targets, without using their onboard radar, which would have ruined their overall stealthy signature, because of a 50-year plan to develop a full suite of infrared-based sensor systems.

Evolutionary Development: Competing on the Edge

The story, of course, is fantasy. However, the only portion of the story that really stretches reality is the 50-year plan to develop IR systems. There has been a research and development (R&D) effort to develop infrared (IR) systems for tactical aviation ever since the end of WWII, but it was not an orderly planned process. Much like natural evolution, the technology-based evolution of infrared systems has produced a diversified, sophisticated set of systems for the military that looks, only in hindsight, as if it was all planned from the start. This analogy to natural evolution as a way to develop systems is currently in vogue in the business world, as evidenced by the full-page ad depicted in figure 1 from the Wall Street Journal.[2]

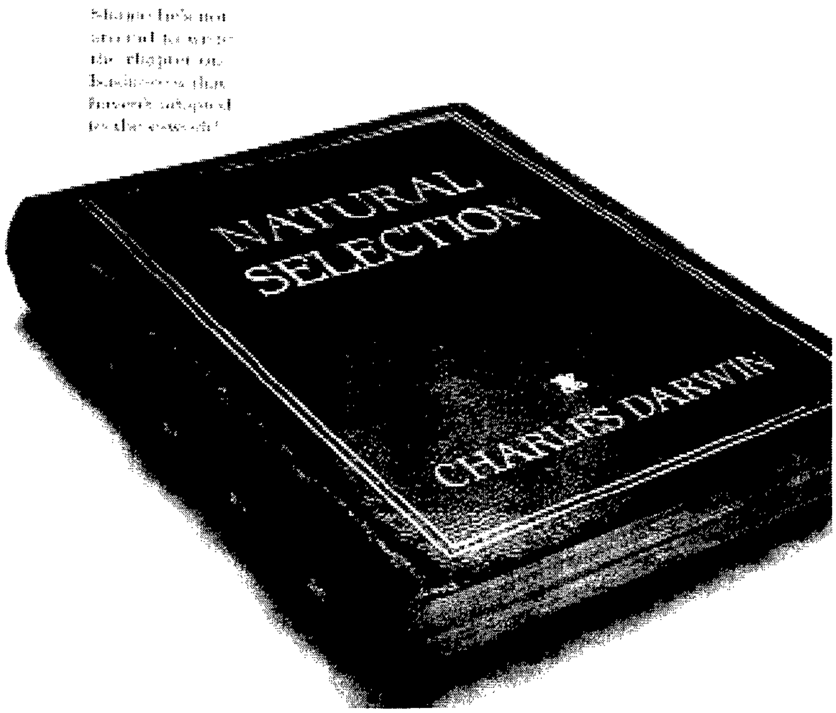

Figure 1: Wall St. Journal Business Evolution Ad

Evolutionary development is based on continuous experimentation and adaptation to changing circumstances. It rewards success and allows, but then eliminates, failure. It is agile, flexible, quick reacting, and thrives on change. In the business world of the future, driven by the Internet, it is portrayed as the development paradigm of the future. It is contrasted against the paradigm of strategic planning where systems are developed in a planned and orderly fashion to meet long term projections of what will be required in the future. A planned system is rigid, slow reacting, and resists or ignores change. It is how the military traditionally develops weapon systems through its planning, programming, and budget system.

If one word can be used to differentiate between evolutionary and planned development, it is "chaos." Chaos is not a term anyone usually wants associated with national defense or the spending of public tax dollars. However, the evolutionary development paradigm suggests that chaos, like risk, is unavoidable so should be thought of as something to manage, not to avoid. Indeed, a certain amount of chaos is desirable in order to generate the necessary set of adaptations and ideas that can eventually be "selected" to continue evolutionary improvement. The Darwinian concept of "survival of the fittest" can be applied to ideas, systems, and even organizations to stay ahead in a rapidly changing world. At least, this is the thesis proposed in the book, *Competing on the Edge: Strategy as Structured Chaos*, a leading text on applying evolutionary and chaos theory to business models. Competing "on the edge" is "the unpredictable, often uncontrolled, and even inefficient strategy that nonetheless defines best practice when change is pervasive." Or, at least, that is the claim of the authors.[3]

A simple example can illustrate their basic line of thinking. IBM is often faulted for not anticipating the switch away from mainframe computers and remote terminals to smaller stand-alone, and eventually personal computers. This can be, and often is, cited as an example of poor strategic planning. Looked at from an evolutionary paradigm, the argument would be that it was *impossible* for IBM to logically deduce such a radical development so no strategic plan could have served them well. Instead of focusing on poor planning, the right lesson learned for IBM is the need to have an organization that is "chaotic" enough to have development in all relevant fields with the ability to adapt quickly when the "fittest" systems survive. Since chaos is not a term usually associated with the buttoned down culture of the IBM of the 1980's, their failure after a radical shift in their business environment is not surprising from an evolutionary standpoint.

If we substitute the Department of Defense (DoD) for IBM and the fall of the Berlin Wall for the PC revolution, a very similar story could be told in the "business" of national security. As we struggle with the post-Cold War security environment and attempt to plan our way into a "revolution in military affairs," based on the radical shift to an information-based society, might the chaotic evolutionary development paradigm espoused in *Competing on the Edge* be a better guide for military modernization?

To forestall inevitable questions about this thesis, the two terms critical to this paper, "chaotic" and "evolutionary" need to be clearly defined. Chaotic does not imply total unpredictability or "a state of utter confusion," as defined in Webster's Dictionary. It should be thought of in terms of the new science of chaos theory, where order and stability can come from inherently unpredictable states, such as predicting the future. For the purposes of this paper, it is useful to think of *chaotic as implying "unplanned" or* *"other than planned."* Evolutionary development is also often misunderstood. It does not necessarily imply a "process of gradual and relatively peaceful advance," one of the definitions in Webster's. Again, the scientific, rather than the common definition applies to this paper. *Evolutionary development is the adaptation of systems to a changing environment by an unbiased selection process that rewards success.* It can lead to radical, as well as gradual, shifts in a system.

Overview

To examine the potential of chaotic evolutionary development for the future, this paper will look at a historical example of military systems development that exhibited chaotic evolutionary traits -- the development of infrared systems for tactical aviation. Infrared (IR) system development is a useful example for several reasons. First of all, the development of such systems did proceed in a relatively unplanned manner that exhibited many of the chaotic evolutionary aspects that need to be examined. Second, IR systems are relevant to current USAF operations. Third, IR systems can be examined under the ultimate test of military systems, combat. Fourth, and perhaps most important, the evolutionary development of IR systems can be "benchmarked" against the more traditional planned development of radar systems, which also exploit the electromagnetic (E&M) spectrum for many of the same military tasks.

The paper examines three cases of chaotic IR systems development that cover the cradle-to-grave aspects of DoD materiel activities (development, procurement, and employment) across the spectrum of tactical aviation (air-to-air, air-to-ground, and surface-to-air). Optional sidebars will provide additional details and related examples. The operational implications on tactical aviation due to the chaotic development of IR systems will also be addressed. The lessons learned from examining these cases and their operational implications hold important insights for current air operations and for future development efforts. The chaotic evolutionary development pattern clearly has and should continue to be exploited by DoD. The analogy to natural evolution will be examined, as well as the analogy's limitations. In an epilogue, the paper addresses how the concept of chaotic evolutionary development might be specifically applied to the attempt to plan an information-based Revolution in Military Affairs (RMA).

There are other important purposes that the paper can serve. First, the reader can get a basic understanding of the state-of-the-art (technologically and tactically) in current IR and radar systems. Second, the reader can get a feel for sensor technology trends and the resultant tactical sensor systems that might be developed in the future. Most of the specific information on these issues will be contained in appendices.

Radar: The First Electromagnetic Window for Military Purposes

Until WWII, humans had fought under visual conditions. The only portion of the electromagnetic spectrum humans could "see" in was the extremely small part that the human eyeball is sensitive to (See Appendix A). Optical devices had greatly augmented human vision (binoculars, optical sights, etc.), but fighting was still mostly governed by the limitations of the human eyeball. Soldiers and airmen usually fought at relatively close range, rarely fought at night, were severely limited by smoke, other obscurants, and weather. They could also easily be deceived by camouflage and concealment.

The advent of radar greatly expanded the military's ability to "see" and, therefore, fight under the above conditions. This new "vision" especially impacted air operations. In 1940, radar systems were very primitive but still had a decisive effect on the Battle of

Britain by extending the RAF's "vision" across the English Channel.[4] Under the lash of wartime necessity, radar took great strides in development throughout the war. Radar systems became small and rugged enough to fit on large aircraft, allowing RAF bombers to "image" the ground for "accurate" night bombing (or at least as accurate as contemporary American daylight bombers).[5] By the end of the war, the Germans had developed even smaller radar systems for use on fighter aircraft that limited the bombers' traditional nighttime sanctuary.[6] America was late to the war and lagged in radar development. A year after the Battle of Britain, a developmental US radar system "saw" the Japanese attack on Pearl Harbor while still well out to sea but its "vision" was not acted upon since it was still in developmental testing.[7] America, typical of its "way of war," eventually embraced the new technology. USAAF bombers used radar to "see" through the smoke and haze of the Ruhr industrial area and through the usually cloudy European weather.[8] America developed its own radar-equipped night fighters for the Pacific theater (P-61 Black Widows)[9] and radar-equipped aircraft helped turn the tide against the U-boats in the Battle of the Atlantic.[10] Tactical aviation was not the only wartime beneficiary of radar, of course. Admiral Nimitz, in the Pacific Theater of WWII considered radar as revolutionary as the steam engine.[11]

The wartime success of radar ensured that it would be a heavily exploited technology after the war. Military requirements for lighter radar's requiring less power, with better resolution and for specialty purposes (such as weather detection) readily flowed. The story of radar-based systems since WWII has been one of "tech pull," a term used to signify that military requirements spur the development of technology. However, despite the tremendous advantages this new vision offered for military operations, radar has some serious liabilities and limitations, when compared to vision. These include inherently low resolution, large size and power requirements, and radar's non-intuitive nature. The most glaring difference is the "active" nature of radar systems and their subsequent susceptibility to countermeasures. See Appendix B for more detail.

Infrared: Another Electromagnetic Window for the Military

The infrared portion of the electromagnetic spectrum theoretically offers many of the benefits of radar without its limitations. The infrared spectrum is just outside the visible spectrum (see Appendix A: figure A1) and the concept for design and the imagery produced by infrared systems is relatively straightforward. The systems simulate human vision and the imagery "looks" like a visual picture.

The difference between radar and infrared systems at the end of WWII was that radar was making substantial contributions to the war effort, while the theoretical benefits of infrared systems were still theoretical. The only wartime infrared system in the Allied inventory in WWII was a sniper scope, employed at Iwo Jima, that allowed targeting at night to a range of only 75 yards.[12] The Germans did use some IR searchlights and simple IR vision devices to attempt night armor attacks, but these were largely unsuccessful experiments.[13] Therefore, while radar, as a demonstrated capability, was able to provide "tech pull" to military R&D, IR systems largely had to rely on R&D advances to provide "tech push" to military IR systems. This difference is primarily responsible for the different patterns of development between radar and IR systems.

Notes

[1] Av Week, July 26, 1999, p. 75. This is the goal of DARPA's Advanced Tactical Targeting Technology project.

Notes

[2] WSJ, 5 January 2000, p. A15.
[3] Brown, p. 243.
[4] Keegan, p.92.
[5] Barker, p. 142.
[6] Delve, Chapter 7, pp. 157-181.
[7] Spector, p. 3.
[8] AWC Y2K lecture.
[9] Delve, p. 163.
[10] Keegan, p. 120.
[11] Miller, p. 350.
[12] Hudson, p. 9.
[13] Westrum, p.48.

IR Evolution and Tactical Aviation

Throughout the Cold War, radar systems continued to dominate tactical aviation applications. The potential big war with the Soviets drove most development plans and radar systems had critical roles to play in all the plans. The emphasis was on fighters that could kill Soviet bombers at long range with radar missiles and low flying attack aircraft that used terrain-following radar to avoid the radars of the Soviet integrated air defense system (IADS). Thankfully, that war was never fought. However, since reality did not conform to the development plan, there were many opportunities in DoD for chaotic evolutionary development to occur. IR systems were a prime beneficiary of such developments across the entire range of DoD acquisition activities. In all three areas of tactical aviation, air-to-air, air-to-ground, and surface-to-air, IR systems made chaotic inroads as compliments and potentially competitors to radar systems.

Air-to-Air: Chaotic Development of the Sidewinder

In the 1960's, the F-4 Phantom was the USAF's primary fighter. It was armed with the AIM-7 Sparrow radar-guided missile. The Sparrow had been under development for over a decade as a direct response to military requirements.[1] It was a large, expensive, long-range, all-weather high-tech marvel of a missile, giving the Phantom a marked advantage in the air-to-air combat against Soviet bombers that the planners had been preparing for throughout the 1950's. Not surprisingly, when the USAF found itself fighting an unconventional war in unfamiliar settings, things did not go according to the plan. In the Vietnam War the enemy didn't fly in the weather and restrictive rules of engagement negated the Sparrow's range advantage. The restrictive rules were established after the third Sparrow "kill" was an American aircraft.[2] After that friendly fire incident, the pilots had to establish positive identification visually before firing. Once inside visual range, the enemy's small, maneuverable fighters actually had the advantage. The Phantom didn't have an internal gun and the radar guidance the Sparrow used was poorly suited to close-in, visual dogfighting. This is because the Sparrow did not have its own radar transmitter. It relied on the aircraft radar to guide to its target in a method called semi-active radar homing. This required the attacking aircraft to keep its nose (radome) pointed in the direction of the opposing fighter (see figure 2).[3] At the high closing speeds of modern fighters, the enemy fighters often had a chance to fire their own short-range weapons while the Sparrow was in flight.

In evolutionary terms, the USAF had an unfilled niche in this unexpected environment. The IR-guided Sidewinder missile filled this niche. It was not a product of the standard military R&D process. In a textbook case of chaotic evolutionary development, a small team led by Bill McLean, at the Naval Weapons Center, China Lake, developed the prototype for the Sidewinder not only without official support, but actually against official guidance.[4] With a maverick attitude and a shoestring budget, China Lake demonstrated an infrared-guided missile that had the admirable quality of "fire-and-forget." That is, all the pilot had to do was get the IR seeker head of the missile to "lock on" and then fire it. The missile would guide on the infrared emissions of the target aircraft's jet engines, requiring no further action from the pilot who could get on with finding another target or simply evading enemy counter-action (see figure 2). Even after the Navy adopted the Sidewinder in the mid-50's, the USAF still ignored the IR missile, pointing out that its requirements documents clearly said "all weather" and the

Sidewinder was not, so "that was that."[5] Luckily, that was not that. The Sidewinder was eventually adopted by USAF and it was a huge success. In Operation Rolling Thunder (1965-68), Sparrows accounted for 27 air-to-air kills while the Sidewinder accounted for 29 kills. In the later Operation Linebacker (1971-73), Sparrows accounted for 29 air-to-air kills while the Sidewinder accounted for 52 kills.[6] The Sidewinder consistently had about double the kill ratio (aircraft kills per missile launched) of the Sparrow throughout the war.[7] The Sidewinder was also considerably cheaper than the Sparrow, one estimate putting its development cost at one-tenth that of the Sparrow.[8]

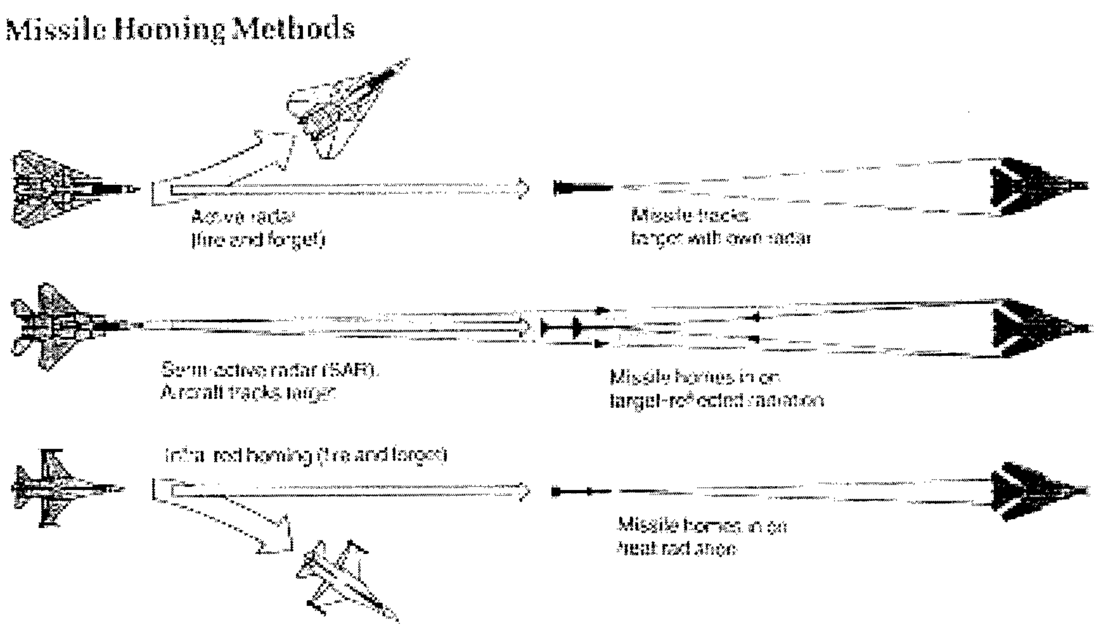

Figure 2: Missile Homing Methods[9]

Air-to-Air: AMRAAM and AIM-9L -- Convergent Evolution

The AMRAAM (Advanced Medium Range Air-Air Missile) was developed to replace the Sparrow in a traditional development program. The program was plagued by the delays and cost overruns commonly associated with such programs.10 However, the AMRAAM is a success story. It is a relatively small "fire-and-forget" radar missile, the Holy Grail of air-to-air missile developers. It depends on a very clever concept which guides to enemy aircraft in three stages. While on the aircraft, it gets target information from the parent aircraft's radar system. The aircraft's fire control system will predict where the enemy aircraft is going and then fire the AMRAAM at that spot. The AMRAAM flies to that spot using internal inertial guidance systems that are very small, cheap, and reliable (and outside the scope of this paper). Not until it reaches the target area does the AMRAAM use its internal radar to get a final fix on the target for terminal guidance.11 So, even though the missile flies out to a long range, it only uses its internal radar for a short range. Therefore, the radar can be small and low power and is only vulnerable to jamming for a short period of time. By merging two different sensing mechanisms, inertial and radar, the AMRAAM designers overcame nearly all the limitations inherent in a radar guided missiles, while keeping all the advantages. Any fighter pilot that previously relied on semi-active Sparrows will testify the fire-and-forget AMRAAM has been a revolutionary advancement in air-to-air weaponry.

The Sidewinder, after its success in the Vietnam War, also became part of the traditional USAF acquisition system. However, it continued to follow an evolutionary development path. An alphabet soup of Sidewinders progressively took advantage of more reliable and sensitive IR detectors until the "L" version produced a quantum leap in capability. The AIM-9L's seeker was so sensitive that it could "see" the heat produced by skin friction on the front of the aircraft and the plume trailing behind. No longer would a pilot have to maneuver to the rear of an enemy aircraft to point his Sidewinders at its hot engine and exhaust. The Sidewinder had become an "all aspect" missile, like the radar guided Sparrow and AMRAAM. One of the test pilots likened it to "a death ray."12 Test pilot hyperbole aside, the all aspect Sidewinder was an extraordinarily lethal weapon. During the Falklands conflict, the AIM-9L transformed the air-to-ground British Harriers into potent fleet defense interceptors, destroying 18 Argentine planes with only 26 missiles for an amazing 75% success rate (two missiles were fired in salvo at the same target).13

As a more traditional development project, the Sidewinder lost some of its cost advantages from its "chaotic" development days. A double entendre joke circulated at China Lake, complimenting the AIM-9L's effectiveness while slighting the costs of a traditional development program: "Bill McLean wanted the Sidewinder to be worth its weight in silver, but they [sic: USAF and Navy] made it worth its weight in gold."14

Air-to-Ground: Chaotic Procurement of LANTIRN

After the success of smart bombs late in the Vietnam War, the USAF set out to develop a wide range of "smarter" munitions. The Maverick Imaging Infrared missile was a natural upgrade from the TV-guided Maverick of Vietnam vintage. It was able to "see" at night and through smoke, significant deficiencies identified from the Vietnam War. The problem with both of the Maverick types was that they required significant attention from the weapons officer to select and lock on to targets. As the USAF moved away from the F-4 and filled its inventory with single seat A-10's and F-16's, the weapons officer became a rare breed. Therefore, the story of the Maverick IR missile is really the story of the system that was supposed to make it usable in combat for the post-Vietnam USAF – LANTIRN.

The LANTIRN system consisted of two pods that could be retrofitted to existing aircraft to give them a night attack capability against armor, a force multiplier for the quintessential planner's scenario of a Warsaw Pact thrust through the Fulda Gap in (then) West Germany. LANTIRN is one of the military's better acronyms, Low Altitude Navigation and Targeting InfraRed for Night. To "see" at night, use LANTIRN, get it? LANTIRN was designed to enable F-16 and A-10 pilots to search for and engage tanks at night.[15] One pod provided a laser range finder and Maverick missile handoff system, while the other pod provided night navigation capability. The navigation capability consisted of an infrared picture displayed on a wide-angle head-up display. The pilot could look through his display and "see" the outside world. In the mid-80's, the first LANTIRN flight simulator for the F-16 was developed at the AF Human Resources Lab at Williams AFB, Arizona. It was a state-of-the-art simulator with a fully functional cockpit, wrap-around visual display (although there was not much to see in a night scene), radar imagery on the heads-down display, and simulated LANTIRN infrared imagery, correlated to the radar and visual scene. The simulator was a key part of a very impressive and successful traditional development effort.[16]

When operational F-16 pilots were brought into the simulator, they were much less enthusiastic than the development team. They informed the developers that flying off the IR image was like "looking through a soda straw," while being color-blind and lacking depth perception. Yet, they were supposed to use this system to fly at high speed near the ground while navigating, avoiding the terrain, scanning for threats, and, eventually, engaging targets. They noted that a good pilot might be able to do 2 ½ of those four tasks. This meant they could survive by not completing the mission or they could attack the target if they adopted a kamikaze-like attitude towards enemy threats and ground impact.[17] LANTIRN was a technical marvel of the USAF acquisition system (and a heck of an acronym) but it had a flawed operational concept. It didn't make it to the 1980's F-16 and A-10 aircraft it was designed for.[18]

Although LANTIRN was a failure as a planned improvement to existing attack aircraft, it eventually became a success when it was adapted to fill a niche in the conversion of the F-15, an air superiority fighter, in the late 1980's. When the F-15 Eagle was being designed in the 1970's, a banner hung in the program office stating "not a pound for air-to-ground."[19] The Eagle was to be a "pure" air superiority fighter unsullied by attack duties. However, a later model of the F-15, the F-15E Strike Eagle, became (and still is) the USAF's premier attack aircraft. The keys to its "revolutionary" change in mission were the addition of a second seat, some tweaks to its radar, and the addition of LANTIRN pods. Two aviators could accomplish the four tasks of navigating, avoiding the terrain, scanning for threats, and engaging targets that the single seat F-16 and A-10 pilots could not. This chaotic merger of the F-15 airframe and LANTIRN pods would prove itself to be a great operational success in the 1990's.

Surface-to-Air: Chaotic Employment of the Stinger

In December 1979, the Soviet Union staged a military coup d'etat against an unstable government in the neighboring country of Afghanistan. This began a nine-year conflict pitting the Soviets and the puppet regime they installed against Muslim freedom fighters, known as Mujahideen. The Soviet military and its advanced technology fought primarily against small bands of poorly armed guerrilla fighters. Nevertheless, reminiscent in many ways of America's Vietnam experience, the Soviets suffered a severe strategic defeat.[20] Much of the credit for the Soviets' defeat goes to the introduction of the Stinger missile into the conflict.

The Stinger is a small IR missile developed and procured for the US Army to give its infantrymen a manportable air defense capability. The US Army has never fired them in anger. The Stinger is the surface-to-air equivalent of the Sidewinder. It is very effective. It is so effective that the CIA initially advised against supplying Stingers to the Mujahideen.[21] However, after CIA-supplied Soviet Strella and British Blowpipe missiles failed to significantly curb the use of Soviet airpower, America supplied Stingers to the guerrillas.[22] The Stingers had an immediate effect on the conflict. Soviet air losses, especially of helicopters, rose sharply, eventually reaching nearly 2000 aircraft lost. Soviet fighter aircraft were forced to high altitude operations that severely limited their effectiveness. Eventually, the Soviets were forced to severely restrict their air operations, removing one of their trump cards in the conflict.[23] The Stinger clearly had "a powerful tactical, if not strategic, impact on the Soviet decision to withdraw from Afghanistan."[24] The Soviet defeat in Afghanistan was one of the primary contributing factors to the decline of the Soviet military in the late 1980's and even to the eventual dissolution of the Soviet Union in the early 1990's. Of all the planned major weapon systems that the US developed to defeat the Soviets, the relatively cheap and simple Stinger, in its chaotic role as a guerrilla war weapon, did far more than its fair share.

The Stinger's unplanned success is only part of its chaotic story. Just as pertinent are the second- and third-order chaotic effects that are now coming back to haunt the US. The Taliban, successors to the Mujahideen of Afghanistan, in power partly because of American intervention, now shelter Usama-bin-Laden, America's most wanted terrorist.[25] The Chinese, often suggested as our next peer competitor, have increased their military capability by copying Stinger technology supplied by the Pakistani's, who were used to funnel the Stingers to the Mujahideen. As partial repayment, Pakistan got advanced missile and nuclear technology from China and, in turn, proliferated that technology to North Korea to update its SCUD missiles that directly threaten American troops. It is unclear just how far this chain of chaotic proliferation goes (even Somali clansmen were rumored to have Stingers)[26] but the large scale, unintended consequences of the decision to supply Stingers to the Afghans is a perfect example of the "butterfly" effect mentioned so often in popular chaos theory texts.[27]

Surface-to-Air: Yom Kippur -- Predators Encounter a New Environment

In the Yom Kippur War of 1973, the surface-to-air engagements were the critical factor in the air war. During the war, no single Arab surface-to-air system was particularly effective. The Arabs launched 2000 to 3000 radar missiles to knock down approximately 40 Israeli aircraft.28 They launched over 5000 SA-7 Strella's which killed only 30 to 33 aircraft.29 But the SAMs were effective enough. As summarized in Cordesman and Wagner's Lessons of Modern War: "Even though kill rates were low, the Arabs were pleased at the way their Soviet SAMs kept the IAF [sic: Israeli Air Force] at bay."30 This was because the Israeli's were forced to shift their ground attack missions from support of the army, their planned role, to counter-SAM missions. While they eventually killed many SAMs, "the suppression effort took so long that much of the IAF's air superiority could not be brought to bear [sic: on the ground battles]."31 The chaotic diversion of effort nearly cost the Israeli's the war.

In the Vietnam War the USAF faced radar missiles in the north and IR missiles in the south. In the skirmishes over the Suez Canal in the years prior to the Yom Kippur War, the Israeli's had dealt successfully with Egyptian radar missiles. However, in the Yom Kippur War, for the first time, a Western air force had to face a "massive, integrated SAM and anti-aircraft gun air defense network."32 The tactics and training that had worked for the Israeli's in the past were no longer effective in this new threat environment. In particular, the tactic of low level flight to avoid or break radar contact was invalidated in the face of a potent low altitude threat system.33 Because of the need to press their ground attacks early while the Israeli Army mobilized, there was no time for the IAF to adapt to the changed environment. A rapid resupply effort by the Americans, which included some of the latest electronic countermeasures, allowed the IAF to recover.34 However, only the disruption of the air defense network by the advance of the ground forces late in the war finally allowed the IAF to operate the way it was intended.35

Notes

[1] Ibid., p. 46.
[2] Ibid, p. 213.
[3] Gunston (Modern Air Combat), p. 41.
[4] Westrum, p. 113, 119.
[5] Ibid., p. 136
[6] Westrum, p. 215.
[7] Ibid.
[8] Ibid., p. 209.
[9] Gunston (Modern Air Combat), p. 188.
[10] Numerous sources. Av Week, Nov 4, 1985, p. 25 is a good example.
[11] Gunston (Missiles), AMRAAM, p. 22-23.
[12] Westrum, p.195.
[13] Westrum p. 218.
[14] Ibid., p.124.
[15] Personal experience: Armored personnel carriers and trucks were not "worth" an attack by a $500,000 IR Maverick – that was real money in 1983.
[16] Personal experience: As project engineer, I "flew" about 150 hours in the simulator and, as a non-fighter pilot (T-38 instructor pilot at the time), was pretty impressed with the LANTIRN system.
[17] Personal experience: Convinced the pilots would love our simulator, we bought 500 LANTIRN T-shirts to sell at a small profit to fund our Christmas party. We sold one T-shirt to the F-16 squadron at Luke AFB that they hung over the dartboard in their ready room.
[18] Citizen Airmen, Feb 99, pg. 12. In an ironic twist, a LANTIRN-like pod called LITENING is a high priority for these same aircraft as part of the Air National Guard and Reserve plan to stay relevant in the twenty-first century.
[19] Apocryphal story now told about the F-22 program office.
[20] Cordesman, Vol. III, pg. 4.
[21] Ibid., pg. 174.
[22] Ibid., pg. 174.
[23] Ibid., pg.176.
[24] Ibid., pg. 177.
[25] Ajami, p. 26: "In Osama bin Laden, and in the phenomenon of the Taliban, the puritanical zealots who have conquered much of Afghanistan, some Arabs saw an American instrument being turned against its creator. It was in the last battle of the cold war, the drawn-out struggle for Afghanistan, that those radicals had been forged. They had been given American-made Stinger missiles and American money and succor. With such tools had bin Laden and his acolytes thwarted communism; now they have turned on the Great Satan. Most Muslims shed no tears for the United States. The Americans, after

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all, had sown the wind in the impenetrable hills of Pakistan and Afghanistan; now they are reaping the whirlwind."

[26] Discussion with LTC Parish, US Army intel officer during US Somali operation.

[27] Gleick, p. 8. The Butterfly Effect is the title of the first chapter of his best-selling book on chaos theory.

[28] Cordesman, Volume I, p. 80.

[29] Ibid., p. 82.

[30] Ibid., p. 82.

[31] Ibid., p. 82.

[32] Ibid., p. 82.

[33] Ibid., p. 85. AAA and especially ZSU-34 are deviations from the story. They were very effective in the low altitude environment, especially when pilots flattened out from the steep dives and split-S maneuvers they used to avoid SAMs. ZSU-34 was expected to be very effective in any scenario in which tactical aircraft had to attack armor on the move. But, first, that scenario never really happened again after the Yom Kippur War. Second, planners ensured ZSU-34 was one of the most heavily countered radar systems, partly because of their demonstrated effectiveness and because many were captured in the Israeli ground campaign (no unclassified source but a reasonable inference).

[34] Ibid., p. 85.

[35] Ibid., p. 84.

Interim Summary

At the beginning of the 1990's, the entire national security situation underwent monumental change. When the Berlin Wall fell and the Soviet Union collapsed, the United States was faced with the unplanned "post Cold War" world. The USAF, its force structure based primarily on defeating a Warsaw Pact invasion that was no longer a possibility, would soon face the challenges of a much more chaotic world. The situation in each of the tactical aviation areas was as follows:

Air-to-Air: No Reasons for Doubt

There was little reason to doubt the USAF's capabilities in the air-to-air arena. The USAF still used the Sparrow but also had the AMRAAM (Advanced Medium Range Air-to-Air Missile) that promised to be far more effective. The USAF also had an upgraded version of the demonstrably lethal Sidewinder.[1] In addition, the Israeli Air Force (IAF) had demonstrated the superiority of Western pilots and aircraft against Soviet proxies in numerous conflicts. In the aerial battles of the 1970's and 1980's, the American developed air-to-air missile systems (and Israeli variants) turned Israeli air superiority into air dominance.[2] With similar training, aircraft, and even better missile systems, there was no reason to doubt the USAF would dominate air-to-air combat.

Air-to-Air: Dominant Predators

The Yom Kippur War in 1973 saw larger air-to-air combat than in any previous Arab-Israeli war. The Israeli's dominated the air-to-air battles because of superior pilots and superior missiles.3 Israel downed 277 Arab aircraft while only losing six in aerial combat. Most of these kills (app. 65%) were due to IR-guided missiles (Sidewinders and Israeli variants). Only 5% were due to Sparrows.4 In the Lebanon conflict in 1982, the Israeli Air Force (IAF) used both IR and radar missiles to even greater effect against the Syrian Air Force. Sparrow missiles were not particularly effective killers but served the tactical purpose of breaking up Syrian formations. The all-aspect Sidewinder was a major qualitative advantage for the IAF and accounted for most kills.5 When superior situational awareness from airborne warning and control platforms (variants of the US Navy's Hawkeye) was added to the traditional missile and pilot superiority, the results went from one-sided to total dominance. The lopsided ratio of 85 aerial victories to zero speaks for itself.6 The Syrians eventually considered missions against the IAF as virtual suicide missions. Some Syrian pilots began ejecting at the first indication from their radar warning receivers.7 The air-to-air "turkey shoot" was spectacular and confirmed Israeli mastery in air-to-air combat that had been demonstrated in previous wars.

Air-to-Air: The Sidewinder Evolves into a Python

The IAF used the Sidewinder with great success. Their wartime experience led to a modification of the missile that is a testament to its accuracy. When the Israeli's first used the Sidewinder, one of the primary enemy aircraft often encountered was the MiG-23 Flogger, in its many variants. The Soviets build robust aircraft and even by Soviet standards, the MiG-23 is a robust, sturdy airplane. The Israeli's found that the Sidewinders were so accurate that they often flew into the tailpipes of the Floggers' hot jet engines. The Floggers' engines were destroyed but they contained the blast of the small Sidewinder warhead. This meant the pilot often was able to bail out of the Flogger and return to fight another day. In any air force, the pilot is an integral part of the fighter system. In Arab countries, trained, let alone skilled, pilots were at a premium while oil dollars could easily replace aircraft. Letting the most critical part of the Arab fighter system escape an air-to-air engagement was not acceptable. Therefore, the Israeli's adapted the Sidewinder to accommodate a larger warhead and renamed it the Python.8 When the Python struck a MiG-23, the organic component of the fighter system went down with the plane.9

Air-to-Ground: Untested Possibilities

Most of the air-to-ground development efforts during the Cold War centered on high tech attack aircraft designed to penetrate the radar threat of the Soviet IADS. The B-1 Lancer was a fast low flier designed to go under radar coverage. The F-117 Stealth fighter was designed to be "invisible" to enemy radar.[10] But there were reasons to doubt America's high tech air force. The B-1 was well known as a "hanger queen" with serious maintenance problems and insufficient electronic countermeasures.[11] Also, the F-117 Stealth Fighter's bombing of an unoccupied field during America's Panama operation in the late 80's was a less than auspicious combat debut.[12] In addition, the development of air-to-ground munitions had been neglected so the modern, high tech aircraft would be dropping a mix of dumb and smart bombs little different from that used near the end of the Vietnam War. Therefore, when conflict came in the 90's, there was reason to doubt the value and wisdom of the USAF's investment in high technology attack aircraft that had been primarily designed to penetrate a Soviet IADS that no longer existed.[13]

Surface-to-Air: A Mixed Message

The ability of the USAF to operate in a surface-to-air threat environment was cautiously optimistic. In the Bekka Valley in 1982, the Israeli's had shown that a radar-based integrated air defense system, which had given them so much trouble in the Yom Kippur War, could be beaten and that older generation IR missiles were not much of a threat since they were easily decoyed.[14] But the single experience of the Bekka Valley could not easily be extrapolated to the situations the USAF might face. The entire engagement over the Bekka Valley was over so quickly and apparently effortlessly that it seemed more a lesson in Israeli martial prowess and Syrian incompetence than it did a true test of air defenses.[15] In addition, the Israeli's were intimately familiar with the combat area and their opponent. They had practiced their attack on the Syrian air defenses for nearly a year in the Negev desert.[16] Such a situation was highly unlikely for US forces facing a chaotic world in which threats might arise anywhere and at any time. To further complicate matters, the Afghanistan conflict had shown that modern IR missiles could be extremely effective even when used in small numbers in a primitive air defense system. Although the USAF had put great effort into developing platforms that could survive the SAM threat, the issue was still in doubt as America headed into its first conflict in the post Cold War world.

Surface-to-Air: Near Defeat Spurs Adaptation and Evolution

The short timeframe and critical requirement for early close air support prevented the IAF from experimenting and adapting during the Yom Kippur War. During the next major conflict between the IAF and Arab SAMs, over the Bekka Valley in Lebanon in 1982, the Syrians employed nearly the same mixture of air defense assets that had been so successful in 1973: radar-guided SA-2/3 and SA-6 long-range missiles were integrated with SA-7 infrared missiles and numerous types of AA guns. The IAF was not caught unprepared this time. Lessons of Modern War summarizes the results: "Unlike 1973, the IAF made SAM suppression one of its most critical objectives of the war. It was so successful in this area that it becomes difficult to discuss any aspect of performance by the Soviet SAM systems in Syrian and PLO hands."17 It was an amazing turnabout. The Israeli's nullified the heat-seeking Strellas with flares and thermal balloons, losing only one aircraft to SA-7's despite many low level attacks.18 Their domination of the radar-guided missiles was even more spectacular. The IAF destroyed 17 of 19 Syrian SA-6 sites and several SA-2/3 sites in no more than 20 minutes of active combat.19

Although Israel has used security and deliberate misinformation to protect its radar SAM-defeating secrets, the basis of its success is well known. The Israeli's had superior pre-attack intelligence on the location and emission characteristics of the Syrian SAMs. They began the attack with remotely piloted vehicles, some with sensors to pinpoint the missile sites, some as decoys to entice the radars to emit, and even some with lethal warheads that homed in on the radar emissions. Once the sites were located, a well-coordinated attack plan was executed with the help of Hawkeye airborne warning and control aircraft. The attack aircraft were well protected with the latest countermeasures to include support from large dedicated (Boeing 707 variant) electronic countermeasures aircraft. Even some surface-to-surface missiles and artillery shells were specially designed to attack air defense radars.20 No Israeli aircraft were lost and, at the very start of the conflict, the Syrian air defense system was effectively destroyed.

Notes

[1] Westrum, p. 197.
[2] Cordesman, Vol. I, p. 85.
[3] Cordesman, Vol. I, p. 85.
[4] Ibid., p. 86.
[5] Ibid., p.201.
[6] Ibid., p. 201, 91.
[7] Ibid., p.201.
[8] Gunston (Missiles), p. 42. A poor choice of snake for a nickname – another IR sensing snake like the Sidewinder would have been a much better choice.

[9] Personal experience: conversation with Israeli exchange officer. The Israeli's had the same experience with the Maverick air-to-ground IR missile, but made exactly the opposite modification. The Maverick was also very accurate, consistently scoring direct hits on tanks. Since it is a massive missile impacting with high velocity on the vulnerable top armor, the kinetic energy of the impact was sufficient to kill a tank. The exploding warhead was superfluous, unless, as the Israeli's noted, you wanted to blast the already dead tank into shrapnel to kill dismounted infantry in the vicinity. Being practical warfighters, the Israeli's took the warhead off some of their Mavericks for a substantial weight savings. This increased the range and/or payload of the parent fighter and the range of the Maverick missile itself.

[10] Grant, p. 27. Stealth aircraft are not really invisible to radar. The goal of stealth technology is to decrease the effective detection and tracking area of the radar.

[11] Numerous sources. Av Week, Nov 5, 1992, p. 70 is a good example.

[12] Numerous sources. Av Week, Jan 1, 1990, p. 32 is a good example.

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[13] Av Week, Mar 22, 1999, p. 57. Describes problems with integrating elements of ex-Warsaw Pact IADS into NATO structure.

[14] Cordesman, p. 186.

[15] Ibid., p. 193.

[16] Ibid., p. 187.

[17] Ibid., p. 186.

[18] Ibid., p. 186.

[19] Ibid., p. 193.

[20] Ibid., p. 188.

Operational Implications of IR Systems Development

The American Aviation Wars of the 1990's

When America prepared to fight Iraq in the Gulf War (DESERT STORM), many commentators looked at the Iran-Iraq War for lessons learned to apply to the upcoming war. In hindsight, it is quite clear that the Israeli experiences pitting Western aircraft, pilots, and missiles against Arab forces were the real crucibles for the combat methods and results of the Gulf War. In the air campaigns over Serbia and Kosovo (ALLIED FORCE), late in the 1990's, the trends in the relationship between radar and IR systems and air operations were brought to an unplanned conclusion that has driven fundamental changes in the way the USAF operates.

Air-to-Air: Nolo Contendere

In neither DESERT STORM nor ALLIED FORCE, did the enemy air force, despite being equipped with fairly modern fighters, seriously challenge the coalition air forces. To quote Ralph Peters, "They had mistaken buying the products with buying the productivity."[1] Iraq attempted a few interceptor sorties during the opening days of DESERT STORM but quickly reached the same conclusion as the Syrians had over the Bekka Valley – flying against the Western air forces was tantamount to suicide. Coalition forces shot down 41 Iraqi aircraft, 24 with Sparrows and 12 with Sidewinders.[2] Due to a delay caused by confusion among the large number of coalition aircraft hunting the Iraqi's, an Iraqi MiG-25 may have scored an aerial kill, just before it was shot down.[3] In a sign of how completely the coalition forces dominated the aerial battles, the Iraqi aircraft were not safe even *after* retreating into hardened shelters. In a well-publicized operation, coalition aircraft started to systematically destroy the shelters and anything contained within.[4] The Iraqi's were forced into the truly desperate act of running the gauntlet of coalition combat air patrols so they could escape to Iran, a country they were still technically at war with.[5]

Over Kosovo and Serbia, the story was much the same. Again, the enemy air forces had capable aircraft, such as the MiG-29, but were vastly overmatched by NATO in the aerial battles. The same combination of superior aircraft, pilots, missile systems, and situational awareness tools that had served the IAF so well resulted in one-sided aerial battles until the enemy simply left the field. As with the Israeli experience, there are few lessons to learn from the air-to-air contests of the 1990's other than the West totally dominates the arena.

Air-to-Ground: DESERT STORM – The IR War

DESERT STORM historians have claimed many questionable firsts for the Gulf War: the first Info War; the first RMA war; and/or the first successful air war. Whether or not those are true, DESERT STORM was certainly the first war in which IR systems played a dominant role. The nightly news video showing the Allies' prowess with precision guided weaponry was nearly always from IR systems. F-15E Strike Eagles, only recently equipped with LANTIRN pods, became very popular war-horses and more LANTIRN systems were rushed into theater.[6] Chaotic use of IR systems sprouted throughout the war. The small, low resolution image from Maverick missile seekers, designed with just enough resolution to verify a target, were used instead by A-10 pilots as "mini-LANTIRNs" to search the desert for targets.[7] F-111 pilots were able to use their venerable Vietnam War vintage Pave Tack pods to "plink" tanks because the tanks' armor stayed warm, and therefore highly visible to even low-resolution IR systems, long after the desert sand cooled.[8] The F-117 stealth fighter, the most modern strike aircraft of the war and the undisputed "star" platform, had no radar at all. Following the dictum that a stealthy aircraft should not emit, the F-117 relied on IR systems for navigation and targeting.[9] During Desert Storm, IR systems demonstrated they had evolved to the point where they were critical to the USAF domination of the battlefield.[10]

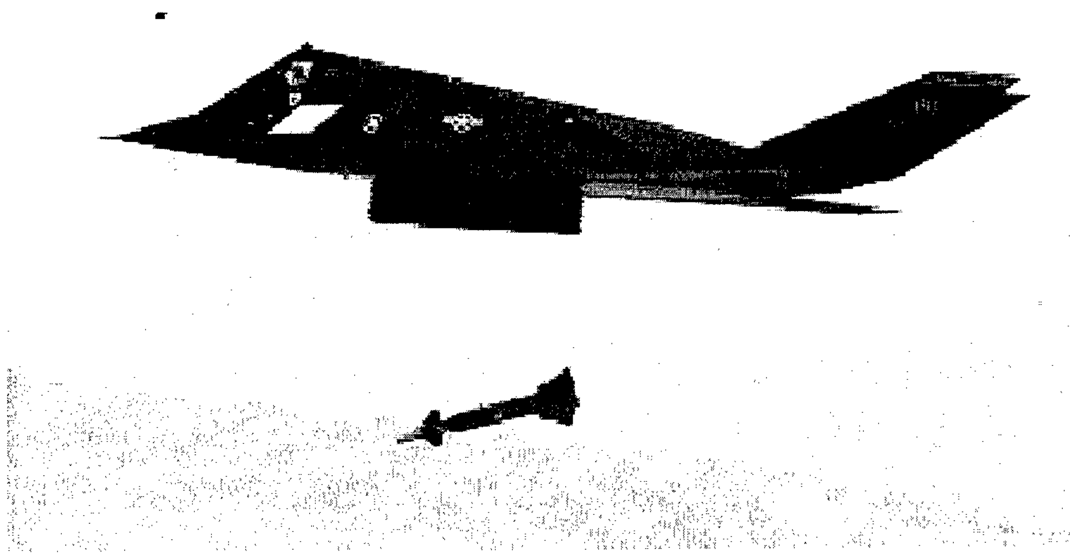

Figure 3: The Stars of the Gulf War (F-117 Stealth Fighter Dropping a GBU-27)

An attack aircraft with IR-based avionics dropping an IR laser-guided bomb from an altitude above the IR SAM threat

Air-to-Ground: Kosovo -- The GPS War

Away from the desert, IR systems' weather limitations became a more critical limitation. The star of the Kosovo conflict, ALLIED FORCE, was not the F-117 and its IR systems, as in DESERT STORM, but the B-2 bomber and the Joint Direct Attack Munition (JDAM). The JDAM is guided by an inertial navigation system using Global Positioning System (GPS) input. GPS, a space-based navigation system, was unaffected by weather so the B-2 was one of the few systems that could bomb through the overcast weather which characterized the first few weeks of ALLIED FORCE.[11] Both the B-2 and the GPS satellite system were big, planned USAF development efforts. Indeed, if high cost is indicative of traditional development programs, then the B-2 may be the epitome of such efforts. If the initial Sidewinder models were worth their weight in silver, and the later models developed by USAF were worth their weight in gold (see earlier section), it is hard to find any elemental yardstick with which to judge a bomber that is routinely characterized as costing $2 billion dollars. But the B-2 and GPS are not really able to carry the standard for planned development efforts.

The initial development and "marketing" of a satellite-based navigation system to the USAF was nearly as tortured as the saga of the Sidewinder.[12] And the B-2 must be counted as an "other than planned" success. The B-2 was designed to drop nuclear bombs on mobile targets (Soviet ballistic missile launchers) during a full-scale nuclear conflict as part of WWIII. Instead, the success of the B-2 was as a conventional bomber striking stationary targets (e.g. bridges, airfields, and the Chinese embassy) during a small-scale conflict as part of a humanitarian operation. Although not as a part of the IR system development story, the systems used to bomb Serbia offer further evidence of the utility of chaotic evolutionary development.

Air-to-Ground: Kosovo -- The Tomcat Evolves

The US Navy's F-14 Tomcat aircraft underwent a radical change between DESERT STORM and ALLIED FORCE. The Tomcat was the epitome of the radar-based fighter aircraft. It is a large fighter because it has a large radar to support a large missile, the AIM-54 Phoenix, that was designed around its own large internal radar. The Phoenix grew from the same radar-focused planning effort that the Sparrow did.13 The Phoenix's large radar, coupled to the highly capable fire control system of the F-14, gave it extremely long range, nearly 125 miles.14 Designed to knock down Soviet bombers and cruise missiles at long range, the F-14 was a dinosaur on its way to extinction when the Cold War ended. The term dinosaur is not used pejoratively. In its time and in its niche (fleet defense), the Tomcat was every bit as fearsome a predator as the Tyrannosaurus Rex was in its time and niche (a Cretaceous carnivore). However, during the Gulf War, the rules of engagement did not allow the extremely long-range missile engagements that the Phoenix/Tomcat combination specialized in.15 The Tomcat was a superb aircraft seemingly without a role to play in the post Cold War world.

Unlike T Rex, however, the Tomcat survived the cataclysmic loss of its prey. The US Navy suffered from a lack of precision guided weapon capability during DESERT STORM and set out to find a solution. By merging the two man Tomcat and its heavy weapons load with LANTIRN pods, the Navy was able to create "Strikecats" in a relatively quick and inexpensive manner.16 Virtually without precision capability in the early 90's, US Navy aircraft were able to effectively participate in ALLIED FORCE, a conflict using almost exclusively precision weapons, by the end of the decade due to a chaotic change of a radar-based interceptor to an IR-based medium bomber.

Surface-to-Air: Air Dominance

It is difficult to compare the Gulf War and the Kosovo conflict to the USAF's previous experiences over Vietnam in the surface-to-air arena. Quantitative percentage figures of types of kills are not relevant because of the different nature of these air wars.[17] A much more relevant comparison is the qualitative observation that radar missiles were a constant danger over North Vietnam and IR missiles were a dangerous threat to low flying, slow aircraft, especially helicopters, in South Vietnam. However, in the Gulf War, as over the Bekka Valley, the enemy air defense system was effectively destroyed in the opening minutes of conflict. The same synergistic use of superior intelligence, radar-baiting decoys, electronic countermeasures, well-coordinated command and control, anti-radiation missiles, and conventional attacks (in the US case, a combination SOF/Apache helicopter raid), used in parallel, simultaneous attack against the entire air defense system resulted in a quick, overwhelming victory.[18] After the first few days of suppression of the Iraqi air defenses, there was virtually no radar missile threat.[19]

However, the Gulf War IR missile threat was much *greater* than during Vietnam or the Israeli conflicts and it persisted throughout the war because the Allied air forces had no way to suppress or destroy the passive IR systems. The Allied air forces, like the Soviets in Afghanistan, chose the tactic of remaining at medium-high altitude to avoid the IR threat.[20] In the decade since the Gulf War ended, Allied aircraft enforcing the no-fly zones set up after the war, continue to attack radar missile sites with virtual impunity while staying at altitudes above the IR missile threat. In Kosovo, the trend of a lowered air defense threat continued. The truly amazing statistic of no Allied aircrew losses and only two aircraft lost to enemy air defenses during a 79 day air campaign speaks for itself. However, once again, Allied aircrews were forced to conduct operations from altitudes above the IR threat. The medium altitude attacks on tactical targets in Kosovo (versus the strategic attacks in Serbia proper) were routinely criticized for their lack of effectiveness.[21] As in the Afghanistan conflict, relatively simple and cheap IR missiles seriously eroded the effectiveness of a modern air force.

Surface-to-Air: Apaches in the Wrong Environment

The most glaring example of the doctrinal disconnect with reality are the lessons "learned" about the Apache fiasco (Task Force Hawk) during ALLIED FORCE. The current thinking is that the Army must make its helicopter deployment lighter and leaner so we can get an Apache strike force incorporated into the air campaign plan. This is exactly the wrong approach. There is no lesson to be learned from Task Force Hawk's misadventures other than the Army had it right. Low, slow-flying aircraft cannot survive in the face of unsuppressed low altitude threats, especially IR missiles. The Army obviously understands that since there is no way to locate the passive IR systems, the only way to suppress the threats in an area of Apache operations is to blanket the area with shrapnel to kill or damage any "soft" targets which might be wielding the systems. That is why the Army deployed the Multiple Launch Rocket System, which really caused the logistical nightmare, with Task Force Hawk.22 After a devastating rocket artillery strike, the Apaches can safely fly in and "take out" the remaining hard targets. This is perfectly sound doctrine under the prevailing IR threat situation. The flaw in the plan is that blanketing a large area with shrapnel is unlikely to be approved as a tactic during a "humanitarian" conflict, such as Kosovo. Therefore, the lesson to be learned from Task Force Hawk is to leave the Apaches home unless you are contemplating a very high level of conflict. Any misguided attempts at jointness that attempt to bring the Apaches into an air campaign as the only platform that has to operate in the unsuppressed low level IR threat environment have completely missed the real "lessons learned" in the air campaigns of the last decade.

Notes

[1] Personal experience: AWC speaker, Sep 99.

[2] Cohen, pp. 653-654.

[3] Keaney, p. 58 footnote.

[4] Murray, p.180. Eventually 375 of 594 (63%) of the shelters were destroyed.

[5] Keaney, p. 18.

[6] Keaney, p. 201.

[7] Almond, p. 21

[8] Murray, p. 188.

[9] Almond, p. 52.

[10] Almond, pg. 285. A significant use of IR technology during DESERT STORM was not for tactical aviation and did not receive much publicity. The "thermal sights" employed by US armor forces seemed tailor made for the ground battles of the Gulf War. Both sides' armor forces had large caliber, high velocity cannon that could engage targets at long ranges. However, the key to modern armored conflict is usually not how far the gun can shoot, but how far the sensors can detect, and hopefully identify, opposing armor. The sand and smoke on the battlefields of the Gulf War were transparent to the thermal sights of US Abram's, Bradley's, and Apache's. While US forces could pick off Iraqi targets at long range, the Iraqi's were reduced to firing nearly blind at the occasional muzzle flash that penetrated the otherwise opaque atmosphere.

[11] Av Week: May 3, 1999, p. 66.

[12] Interview with Lt Col Beth Kaspar – DARPA Program Manager.

[13] Westrum, p.27, 190.

[14] Gunston, p. 44.

[15] Gordon, p. 218. An AWC speaker confirmed the Navy questioned whether rules of engagement were specifically designed to favor USAF's air-to-air capabilities – satisfactorily answered by Joint Forces Air Component Commander.

[16] Av Week, Jun 10, 1996, p. 40 (cover story).

[17] Keaney, p. 61. In the Gulf War, radar SAMs accounted for 16% of the Allied losses, while low altitude defenses (IR missiles and AAA) accounted for 71%. In the Kosovo conflict, radar missiles accounted for both (100%) of the Allied losses.

[18] Ibid., p. 240.

[19] Ibid., p.230.

[20] Even so, the single largest aircrew loss, an AC-130 aircraft, was due to an IR missile that was able to pick up the contrast of the large aircraft against the morning twilight sky (a time of day when the Gunship should not have been in a threat area).

[21] Numerous sources. Av Week, May 17, 1999, p. 31 is a good example.

[22] Av Week: Jun 28, 1999, pg. 36.

Current State of E&M Systems and Tactical Aviation

Air-to-Air: The Top of the Food Chain

The most telling statistic of the air-to-air dominance of the USAF is that a Western piloted F-15 or F-16, the backbones of USAF's air fleet, has *never* been shot down in air-to-air combat.[1] Much of the credit for this dominance must go to the development of air-to-air missiles guided by radar and IR sensors.

The AMRAAM, first used in the Gulf War, is still the state-of-the-art radar-guided missile. While minor improvements in lethality, range, and electronic counter-countermeasures are undoubtedly being pursued, it is not clear that a "better" radar-guided missile ever needs to be developed. AMRAAM may be at an evolutionary dead-end for the same reason sharks and alligators are. It is magnificently successful in its niche.

The all-aspect Sidewinder has been just as successful in its niche. A long running program to replace the Sidewinder with an ASRAAM (Advanced *Short*-Range Air-Air Missile) or AIM-9X has not resulted in any improvements worth pursuing.[2] However, the air-to-air IR guided missile is practically guaranteed one more evolutionary improvement. This improvement will not be based on evolutionary technology trends, as it has in the past. It will be based on the threat-driven requirement of the MiG-29 and its AA-11 Archer.[3] The USAF will **not** have the world's second best IR missile system.

Air-to-Air: Surprise Threat Spurs Evolution

Radar systems depend on electronics and computational power, two fields in which the Soviet Union fell far behind the West in the 1980's. Soviet radar systems were inferior and they had little hope of keeping up on the electronic countermeasure treadmill. Not surprisingly then, the Soviets relied more heavily on more reliable, easier to design, computationally simpler, and tougher-to-jam IR systems. Actually, it *was* a bit of a surprise to Western intelligence. When the MiG-29 Fulcrum was fielded in the 1980's it had a radar system and associated missile that were impressive by Soviet standards but at least a generation behind Western systems, as was expected. It also had a bump on the nose whose function took a while to figure out. The bump turned out not to be an electronic warfare antenna as first deduced, but an Infrared Search and Track System (IRST), the first fielded in an operational fighter.[4] Since it was merged with a laser range finder, the IR system could detect aircraft *and* provide targeting data at long range without alerting the target aircraft that it had even been detected. Even if the target aircraft suspected it was being tracked, there is really no practical way to "jam" such an IR system. The Soviets were solving the electronic countermeasure treadmill problem by simply getting off! Worse IR surprises were to follow.

The MiG's IR system was mated to an improved IR missile. The AA-11 Archer not only had the all-aspect feature of the latest Sidewinders, it also had "off-boresight" capability. This meant that the missile could "look" to its left and right to "see" target aircraft. That meant the Soviet pilot could fire his missile without pointing his nose at the target aircraft, as Sidewinder equipped pilots have to do. This expands the firing envelope for the missile, saving precious seconds in a dogfight and complimenting the maneuverability of a fighter (i.e. it is much easier to maneuver the fighter into firing position). Even worse, the Soviet pilots had a helmet-mounted thermal sight so they could aim the missile merely by looking at the targeted aircraft, in effect giving the Soviets an IR "heads-up display" wherever they looked, not just mounted to the front of the instrument panel, as in Western cockpits. The details of this system did not fully emerge until formerly East German MiG-29's became part of the unified Germany's Luftwaffe. Once they did, it was clear that an IR-equipped MiG-29, flown by a skilled pilot, that met a Western fighter on even terms in a close-in dogfight had an advantage.[5] Putting aside the questions of whether there *are* any skilled MiG-29 pilots left (other than those in Western aggressor squadrons) and how an enemy aircraft can get to "the merge" on even terms when Western aircraft will have vastly superior situational awareness tools and long range missiles, the AA-11 Archer represents a challenge to the technological primacy of the Sidewinder.

It is not clear that the Archer really represents a shortfall in our air superiority capabilities that forces us to adapt in order to remain the "fittest." The USAF advantage in pilot training, situational awareness systems, and long range missiles make an evenly balanced close-in dogfight (other than at USAF training exercises) a highly unlikely occurrence. This was the opinion of the AF general in charge of procurement, as quoted in Aviation Week, while the MiG-29 was being evaluated. And, as he also pointed out, the USAF already has a short range, off-boresight capability inherent in the AMRAAM.[6] However, the USAF acquisition system has been energized by this "IR missile gap" and there is a significant development program within the USAF to develop a US equivalent to the Archer.[7]

Air-to-Air: Vestigial Components

Despite the magnificent missiles of the USAF, the basic 20mm cannon will still be with us for the foreseeable future. Having learned its lessons from Vietnam, the USAF has accepted the engineering complexity and design tradeoffs to ensure that its stealthy super-fighter of the future, the F-22, will be a nimble dogfighter with an internal gun.[8] Of course, that may not have been a lesson to learn. The F-4 *had* to be a dogfighter because USAF lacked the situational awareness tools to handle long-range missile engagements in the 1960's and because semi-active radar homing has serious tactical limitations. However, the F-22 will be firing AMRAAM's, a true fire-and-forget long range radar missile and advanced Sidewinders that will allow short range kills without the traditional dogfighting need to point at the enemy aircraft (a la the AA-11). In addition, the situational awareness tools are available now to solve the air-to-air Identification Friend-or-Foe (IFF) problem that hindered missile engagements during the Vietnam War.[9] At the very least, such tools are part of the information superiority promise of Joint Vision 2010.[10] Under the circumstances of the

1960's, not designing the F-4 to dogfight with the MiG-21 in the MiG's operational envelope was a serious oversight. However, under the current circumstances, and certainly those that will prevail in 2010, designing the F-22 to dogfight with the MiG-21 (which will still be around) in the MiG's operational envelope, could be just as serious a mistake. It is possible to learn the wrong lessons from history.

Air-to-Ground: Evolution by Merger

In DESERT STORM, due to IR systems, the USAF demonstrated a quantum leap improvement in the ability to deliver precision weapons and to operate around-the-clock. Less than a decade later, US forces raised their performance another level by demonstrating unparalleled all-weather performance and nearly total precision. A standard USAF briefing makes the following claims for bomb accuracy (in terms of circular error probable):[11]

1972: 400 ft conventional; 40 ft precision – very few aircraft with capability

1991: 30 ft precision – 10% of the force with precision capability

1999: 10 ft precision – 90% of the force with precision capability

1999: 40 ft precision all weather capability – few aircraft with capability

New systems are on the verge of another breakthrough in performance. "Brilliant Weapons" is the title of an article in the February 1998 Air Force Magazine which details numerous precision standoff weapons that are in advanced development stages and will be in the USAF inventory in the near future.[12] Other systems that can selectively engage multiple targets such as the Low Cost Autonomous Strike System (LOCASS) and the Sensor-Fuzed Weapon are only slightly further behind in development.[13]

Three technology developments are making these weapons feasible now. Low cost IR sensors are now cheap enough to put on expendable munitions, not just on the delivery platforms. The same is true of GPS receivers for inertial navigation. And the microprocessor revolution has done the same for the chips that constitute the "brains" of brilliant munitions. There are two important points to consider when looking at the effect of these developments on the new generation of munitions in chaotic evolutionary terms. First of all, while each technology development is powerful in itself, it is the merging of these three technologies that has true breakthrough potential. Second, the low cost trend in all three technologies, which is the key to using them on expendable munitions, has been driven by the civilian sector, which operates more and more independently from the military aspects of any national security plan.

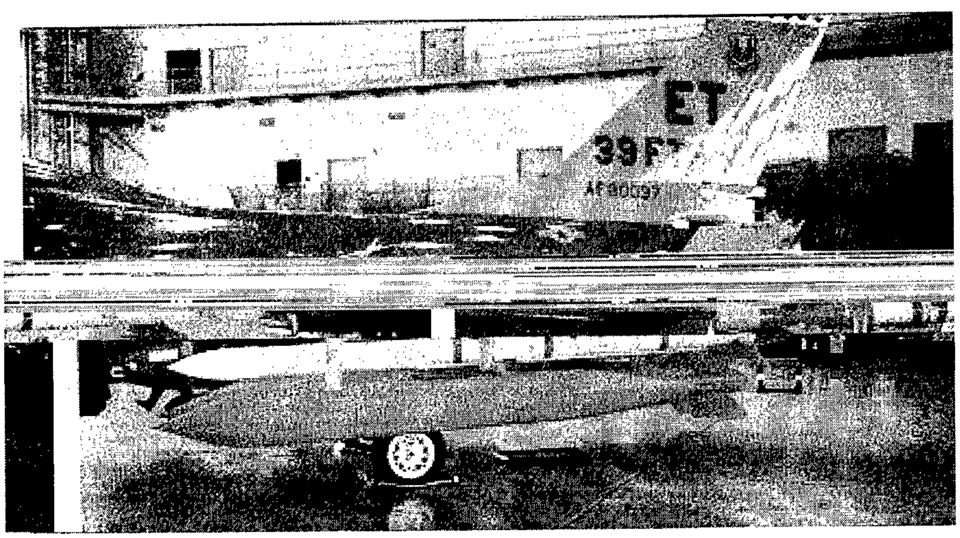

Figure 4: The Top of the Food Chain: F-16 with Sidewinder, AMRAAM, and JSOW

Surface-to-Air: Predators Adjust to a New Environment

It is too simplistic to just look at the lack of losses and claim the USAF has conquered the air defense threat. This is because the job of an air defense system is not to "win" the air battle against attacking aircraft. There is no precedent in the admittedly limited history of aerial warfare for "victory" by air defense assets versus attacking aircraft (although the Egyptians came perilously close to such a victory in the Yom Kippur War). The job of an air defense system is to deny enemy aircraft the use of airspace to prosecute aerial missions. When looked at in this light, it is obvious that there is a huge difference between the current effectiveness of radar and IR missiles. Radar missiles have been singularly unsuccessful against USAF aircraft while IR missiles have been spectacularly *successful.* In the Gulf War, no-fly zone enforcement, and in the air over Kosovo and Serbia, the airspace below 15,000 feet has been virtually off-limits to Allied aircraft. Even though this is a self-imposed limit, the fact remains that the airspace below 15,000 feet is very dangerous due to the IR missile threat (and anti-aircraft artillery, AAA, but that has always been a threat USAF was willing to risk). The danger of the low altitude environment was amply demonstrated by the loss of over a dozen low flying Unmanned Aerial Vehicle's during ALLIED FORCE.[14]

The difference in risk level is not surprising. To combat radar missiles, the USAF has used suppression techniques, jamming capability, stealth aircraft, and even special operations raids (the Pave Low-led Apache attack on early warning radars in the Gulf War) and information warfare (according to Aviation Week and other unclassified sources)[15] to gain a virtual sanctuary in the radar missiles' environment. However, USAF aircraft have limited countermeasure and signature reduction capability against IR missiles and virtually no way to locate, let alone suppress these passive systems.

This trend from recent conflicts is clear. The USAF has virtually conquered the radar threat while ceding victory to the IR threat in the low-level environment. The initial reaction to this state of affairs, as highlighted during ALLIED FORCE, is that it has been an aberration from which few lessons can be learned.[16] However, it is also possible to interpret ALLIED FORCE as the logical conclusion of the USAF's "tech pull" drive to develop advanced radar systems and countermeasures versus its "tech push" approach to incorporating and countering IR systems at whatever pace the technology evolves. If this is true, then ALLIED FORCE is not an aberration, but is the norm for air campaigns to come. This poses serious doctrinal, training, and acquisition issues that the USAF must face.

For now, the USAF has settled on the "non-materiel solution" of flying above 15,000 feet to avoid the IR threat. The USAF acquisition effort to actually counter the IR missile threat is at least an order of magnitude below the attention given to the radar threat.[17] The USAF must make some difficult choices. If the limit of 15,000 feet becomes a semi-permanent tactic, that reality must be addressed doctrinally. USAF pilots will become beyond visual range, standoff, precision weapon shooters in the air-to-ground arena just as they are on the verge of becoming in the air-to-air arena. Low level flying and dogfighting skills, hallmarks of a generation of Cold War fighter pilots, may become all but irrelevant.[18] As a result, there would have to be radical changes in USAF training and tactics.

If the USAF is unwilling to face banishment from low level tactical airspace then it needs to re-evaluate its approach to IR systems. Waiting for a "tech push" solution to appear, as has been the norm, is a poor solution because current technology trends (cheaper sensors and smarter microprocessors) strongly favor the missile developers. There is no straightforward solution to suppressing/destroying passive systems that is on the horizon. Catching up to and then staying ahead of the IR missile threat would challenge a program with the resources and priority of a traditional planned program and the flexibility and adaptability of a chaotic evolutionary program. In other words, it might serve as a perfect test case for DoD development efforts of the future.

Surface-to-Air: Planning for the Wrong Environment?

The airmen that led Allied Force expect the future to bring advanced radar missiles and interceptor aircraft that will challenge USAF air dominance.[19] The USAF is preparing for that threat. Preliminary lessons learned from Kosovo include the need for more and maybe better jamming aircraft (possibly an EB-52), more and better suppression aircraft (possibly an F-22 or JSF Wild Weasel), and continued procurement of the F-22.[20] In addition, the one combat mission that airmen are now not only willing, but eager, to cede to "unmanned" (or uninhabited, in the latest twist of jargon) aircraft is the suppression and destruction of enemy radar air defense systems. These operational requirements are driving tens of billions of dollars in R&D and procurement to ensure the USAF will be even better at meeting the radar threat of the future.

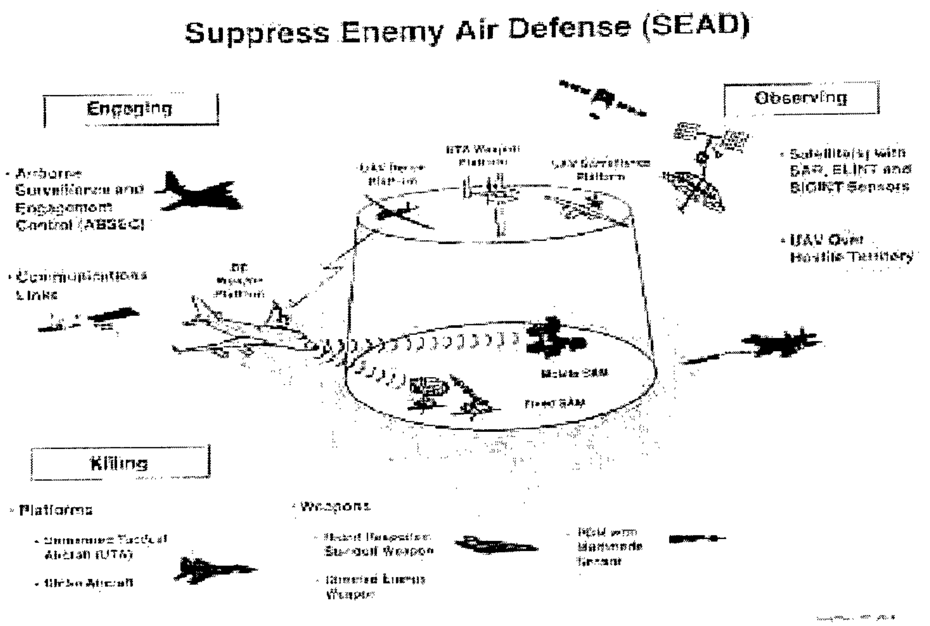

Figure 5: USAF's Future Vision of Suppression of Enemy Air Defenses [21]

But what if the threat does not materialize? Certainly, any regional power contemplating conflict with the USA and its allies may have learned a different lesson than the need to buy advanced long-range air defense systems. Interceptor aircraft and advanced radar SAMs are expensive systems requiring a lot of training and maintenance support. And they don't seem to work. In ALLIED FORCE, the long-range systems were annoyances and inconveniences, forcing even stealth aircraft to plan missions around electronic support aircraft and keeping the pilots on edge.[22] But, the systems had little effect on the air campaign and many of them were eventually destroyed. And, the USAF is on track to getting even better at defeating radar-based interceptors and SAMs (see figure 5 for a USAF vision of future radar defeating systems).

A potential aggressor may also notice that the shorter range IR systems did their job and were virtually unchallenged by the coalition aircraft. What if he put his limited resources towards IR systems? The 15,000 foot self-imposed limit could become a "hard" floor on

USAF operations, to include UAV sensor platforms. By relying on camouflage, concealment, deception, and humanitarian concerns (placement of military materiel in close proximity to collateral damage sensitive sites), a potential aggressor might effectively shield his forces from USAF long-range weaponry. Combined with the ability to jam or spoof at least some of the USAF's precision guided weaponry, an uneasy standoff might result where USAF aircraft were safe above 15,000 feet but unable to effectively strike enemy forces. The current US military strategy, which relies heavily, if not solely, on airpower would be invalidated. Perhaps we would have to test both Sadaam's and Milosevic's strategy of forcing a ground campaign to see if America can stand substantial casualties – a most unpleasant prospect.

Technology: Millimeter Wave – the Crossroads of Development

The millimeter wave (MMW) portion of the E&M spectrum lies between infrared and radar frequencies/wavelengths (approximately 10 – 100 GHz, see Appendix A). Technical evolution has filled the sensing niches in the E&M spectrum above and below the MMW region. There are no other atmospheric windows left to exploit between the visible and radar ends of the spectrum that might provide breakthrough results. IR systems trying to exploit the E&M spectrum below millimeter wave (in terms of wavelength) will be intruding on the niches already well developed by radar. The converse is true for radar systems that attempt to exploit shorter wavelengths than millimeter wave. The millimeter wave spectrum, as the crossover point between radar and IR systems, represents the last untapped region of the E&M spectrum for sensor developers to exploit for tactical aviation.

Fortunately, MMW systems offer great promise. Systems based on the exploitation of the MMW spectrum have the potential to combine the benefits of IR systems and radar systems while minimizing their corresponding limitations. MMW systems can (and are) being developed both as IR and as radar systems. Some innovative MMW system concepts even combine elements of both imaging (IR) and processed (radar) systems. Appendix D contains details on these different approaches and on their potential development for tactical aviation.

Notes

[1] Hallion, p. 65. F-15s and F-16s have shot down 130 enemy aircraft.
[2] Av Week: Oct 16, 1995, p. 36.
[3] Interview with AFRL researcher on off-boresight missile and IRST and HMTS.
[4] Av Week: Oct 16, 1995, p. 49.
[5] Av Week: Oct 16, 1995, p. 39.
[6] Av Week: Oct 16, 1995, p. 38.
[7] Interview with AFRL researcher on off-boresight missile and IRST and HMTS.
[8] Numerous sources. Av Week, Aug 3, 1998, p. 46-48 is a good example.
[9] Keaney, p. 245.
[10] JV2010: Info superiority, p. 16.
[11] AWC Y2K speaker, Jan 2000.
[12] Tirpak, John A., pg. 48.
[13] Personal experience: AWC trip to Eglin AFB for airpower demonstration '99. POC: Ken Edwards; edwards@eglin.af.mil.
[14] Av Week: Aug 23, 1999, pg. 30.
[15] Av Week: Aug 23, 1999, pg. 31.
[16] Av Week: Jun 28, 1999, p. 32.
[17] Personal experience and interviews with AFRL researchers.
[18] Coonts, p. 3. As described in *Flight of the Intruder*, an A-6 pilot would penetrate enemy defenses by flying as low "as his skill and nerves allowed, which was very low indeed."
[19] Av Week: Nov 1, 1999, p. 33. Several AWC speakers reiterated the fear that future enemies would field SA-10/12 and SU-27 Flanker class SAMs and interceptors in response to NATO air dominance during ALLIED FORCE.
[20] Av Week: Jul 26, 1999, p. 70, 75.
[21] New World Vista: Attack Volume, pg.11.
[22] Av Week: Sep 27, 1999, p. 32.

Summary: Chaotic Evolutionary Development in DoD

The unplanned and "other than planned" successes of IR systems for tactical aviation both competed with and complemented the more orderly planned development of radar systems. The most obvious lesson learned from examining the development of these IR systems is that "evolution in military affairs" already exists and Americans are good at it. Yankee ingenuity is alive and well and has been successfully exploited by the military for the IR systems examined in this paper. There is no reason to believe this state of affairs is unique to IR system development. Once the concept of chaotic evolutionary development is understood, many examples of such development in all areas of military systems development can be recognized (e.g. the B-2 and GPS use mentioned in this paper). The terms "Jerry-rigged," can-do, field expedient, and makeshift are commonplace in American war stories. Even the formal military development system has recognized chaotic development with terms such as Quick Reaction Capability (QRC) and Combat Mission Needs Statements. To envision what to expect from such development in the future, it is useful to see how far the comparison can be taken with natural evolution, the most successful case of evolutionary development and the one currently in vogue in the business world.

The Natural Evolution Analogy

The most obvious similarity is that evolutionary development works. In nature, natural selection has produced complex and varied life forms to fill all sorts of specialized niches. In military affairs, combat selection has produced a set of IR systems that perform specialized roles in all facets of tactical aviation. The chaotic development and use of IR guided air-to-air missiles, IR targeting systems, and IR SAMs have had a profound effect on all arenas of aerial combat.

A less obvious, but perhaps more important, similarity is that evolutionary development can produce "revolutionary" improvements in capability. In nature, these "discontinuous" links in the evolutionary chain are now considered a routine part of the evolutionary process.[1] The gradual incorporation of advanced sensor technology into the Sidewinder, once it was in the traditional military development system, led to a discontinuous increase in capability once the seeker head was sensitive enough to view an aircraft from all aspects. This is a classic feature of chaotic systems (i.e. a small change can have large long-term consequences)[2] and is another similarity with nature. It can lead to "revolutionary" changes in the environment itself, such as the Stinger's chaotic effects on military developments well beyond the realm of air defense.

Evolutionary development can also lead to "revolutionary" changes in a system's role in an environment. Penguins probably always ate fish but over time the "fittest" penguins adapted to swimming to catch fish rather than flying. The development of IR systems has already caused a radical change in tactical aviation operations by altering the way USAF aircraft fly and fight. USAF aircraft no longer fly at low level to avoid radar. Cold War low level fliers have become high altitude standoff shooters to avoid the IR threat. This is a radically different method of accomplishing USAF attack missions.

Another useful piece of the analogy is that evolutionary development doesn't always work when and how you logically expect. In *Competing on the Edge*, the authors use the story of artificial prairie development to highlight this point. Agriculturists trying to replicate the Midwest prairie of the American frontier days consistently failed until they simply sealed off the area and let it revert to nature. It turned out that certain weeds, which no rational agriculturist would intentionally introduce to the ecosystem, were vital to its creation.[3] IR system development also highlights this point. LANTIRN development is a similar story of chaotic success. LANTIRN was initially a failure in its planned role of enabling single seat attack aircraft to engage small, high value targets. It eventually became a success after the USAF developed a two seat attack aircraft, the Strike Eagle, and the Navy converted a similar aircraft, the Tomcat. In addition, LANTIRN (and similar derivatives) is now poised to become a success with single seat aircraft because the flying environment has shifted away from the demanding low level flight regime that it was intended for (i.e. a pilot can handle targeting tasks while at medium-high altitude).

Another similarity to nature is that evolutionary development is convergent. Snakes the world over tend to the same basic shape because that shape works well in the snake's evolutionary niche. Canine, feline, and even marsupial land predators (wolves, lions, and the Tasmanian Wolf) tend to be about the same size with the same sort of size, strength, speed, and "arsenal." In the IR system examples, the all aspect radar missile became "fire and forget" with the introduction of the AMRAAM while the "fire and forget" Sidewinder became all aspect with the introduction of the "L" model. Radar developers sought shorter wavelengths for greater resolution (like IR) while IR systems tended to longer wavelengths for greater obscurant penetration (like radar) until they converged at millimeter wavelengths.

The concept of vestigial components is another useful piece of the natural evolution analogy. Human beings have tonsils and an appendix, which are no longer necessary for good health. Although they may perform some useful functions, they are more often seen as avenues for infections and modern humans are generally considered to be better off without them. In air-to-air combat, an advanced off-boresight IR missile will be a true "dogfighting" missile in the unlikely event USAF fighters are forced into close combat. However, the F-22 will still incorporate a 20mm cannon. Like tonsils and the appendix, the internal gun will undoubtedly have some uses but it is doubtful they will balance out the weight, maintenance, and signature problems that will be much more important in modern air operations.

Another piece of the analogy that seems to ring true is that it's not easy to pick the evolutionary winners in the long term. Who would have picked the shrews' and moles' ancestors to out-compete the dinosaurs' descendants? Similarly, the big, powerful radar SAMs that were the primary threat of the Vietnam War are now easy prey for USAF aircraft while the smaller, highly mobile Strella's are masters of their environment. Even in the short term it may be tough to pick the winners if the environment changes. The Israeli Air Force dominated the Mideast skies until all the air defense systems, which the IAF had always defeated separately, were integrated into a single system during the Yom Kippur War.

A final piece of the analogy is obvious to state but has considerable implications in a world in which the US has no peer competitor. As in nature, competition is the main spur to evolutionary development. The accelerated development of radar systems during WWII is one obvious example. The Israeli turnaround from near defeat by an air defense system during the Yom Kippur War to complete domination of similar defenses during the Bekka Valley engagements is another classic example. Competition for the Archer missile is clearly driving USAF development of an AIM-9X.

Un-Natural Evolution

As instructive as the natural evolution analogy is, it is equally important to understand when the analogy breaks down. There are many instances where systems development based on the evolution of technology, as IR systems have been, do not follow the analogy of natural evolution.

First of all, systems development does not depend on random change as nature does. Although this paper stresses the chaotic nature of the development of IR systems, this should not be confused with the truly random mutations that nature depends on for evolution. Unplanned or "other than planned" development successes still had some rational person or organization decide to solve a problem or recognize a solution that others had not seen or did not realize they needed. This is chaotic, but not random. Since systems development does not have millions of years and billions of subjects to experiment with, this is a crucial difference.

Because systems development is rational at some level, there is a distinct difference in which systems evolve. In nature, random change occasionally generates success that leads to evolution. The cycle is out-of-sync and has a crucial difference in systems evolution. It is a well-established military maxim that defeat, not success, drives change. Losers seek change that leads to evolution that may be successful. The most notable historical example is the embrace of the WWI defensive mentality by the victorious French while the defeated Germans developed the radically different blitzkrieg offensive. In the examples in this paper, the Israeli's near-loss in the Yom Kippur War drove them to change their priorities (counter-SAM vs. early ground support) and to develop innovative tactics while the Syrians integrated air defenses remained relatively unchanged. On a smaller scale, the US Navy's limited role in the Gulf War drove them to innovative solutions, like radically changing the role of the Tomcat, in order to quickly and cost-effectively prepare for full participation in future air operations. Since America is the biggest winner of the last decade and Russia is the most conspicuous loser, the un-natural aspect of losers evolving and winners stagnating is an important distinction to consider.

Another important difference is that, unlike nature, systems development based on technical evolution is easier for the second guy. It may be hard to stay on top of the food chain in nature, but it is much tougher in military-technical competition. Natural evolution tends to close out competition in nature as niches get filled -- animals can't just see how a shark became successful, then duplicate its success. For development based on technology evolution, the situation is exactly the opposite. Sometimes the mere knowledge that a technology is possible affords an adversary an advantage, which is one of the reasons the USAF protected its stealth capabilities for so long. Sometimes the new technological development is sold or given away and, as in the case of the Stinger, may end up in unintended and unfriendly hands. And, of course, espionage can sometimes allow a military competitor to catch up in technology evolution. In the case of IR guided missiles, the Soviets developed their Atoll missile directly from stolen blueprints of the Sidewinder. They even copied the Philco company's part numbers.[4]

There is a distressing corollary to the un-natural advantage of the second system to evolve. In the past, even if it was easier for #2 to develop a technology, at least that nearly always meant the US military was first in important technologies. However, since civilian research and development increasingly sets the pace of technology development, this may no longer be true.[5] Now, civilians may be first with a new technology and another entity, not encumbered by a slow reacting, planned procurement system, might be able to adapt to the technology faster than the US can. In IR systems development it is possible that civilians are already ahead of the military in exploiting charged coupled devices (CCD) and uncooled thermal detectors, as evidenced by CCD-based camcorders and the Cadillac Deville's thermal imaging system. These two technologies will allow nearly any military force to field the types of IR systems that have heretofore been such an advantage for US forces. Special operations forces, whose tactical advantage has long rested on night vision devices, now routinely claim, "We no longer own the night."[6]

An important un-natural aspect of systems development evolution is that it can occur by merger. Only in mythology can a lion sprout wings and become the truly formidable Griffon. However, chaotic system evolution by merger is a recurring theme in this paper. AMRAAM made radar guided missiles a stunning success by combining radar and inertial sensors. The Harrier and the Tomcat evolved into entirely different niches when merged with the all-aspect Sidewinder and LANTIRN, respectively. The Egyptian integration of radar and IR SAMs and AA artillery in the Yom Kippur War was a successful merger on a massive scale. Brilliant munitions are an emerging success now that IR sensors can be merged with inertial sensors and cheap microprocessors. Hopefully, IR missile developers will not soon perform a similar evolution by merger.[7]

A less serious, but important, difference is that nature stops at good enough. Systems development based on technology evolution has no natural end. Sharks and alligators have not changed appreciably in millions of years. There is no shark or alligator improvement plan because they have no competition in their niche. The panda's thumb is another natural example of "good enough," as well as the title of a popular text on evolutionary theory by Stephen Jay Gould. The panda's thumb (not really a thumb at all) is very poorly "engineered," compared to a human's opposable thumb. However, the thumb is good enough for gripping and stripping bamboo shoots, the panda's only food source. There is no need and therefore no driving force for the panda to have a better thumb.[8] In contrast, a systems development bureaucracy can become an unnatural driving force for continuous improvement. There are all sorts of bureaucratic reasons, including simple inertia, which can drive systems development past "good enough." In the case of IR guided missiles, the current USAF effort to develop an off-boresight missile system in reaction to the Soviet Archer missile cannot be justified solely on a threat to the USAF's dominance in the air-to-air niche.[9]

The final un-natural difference in systems development evolution is that it can occur by planning. Chaotic development seems to hold cost and time benefits over traditional planned development paradigms but it would be ill-considered to take the natural evolution analogy so seriously that unplanned development becomes the plan. Logic and forethought can and should provide some focus to system evolution. The authors of *Competing on the Edge* refer to the belief that people can consciously affect chaotic evolutionary development as "intentionality."[10] A good rule of thumb seems to be that the less obvious the solution, the more varied the experimentation needs to be and the more flexible and adaptable the organization needs to be. If a practical solution to a straightforward problem can be planned, there is no reason not to pursue it. The evolution of the Israeli Python from the Sidewinder is an example of a practical and efficient solution to a straightforward problem.

Conclusions

Orderly planned development is the preferred method for DoD and it gets the vast bulk of resources. Planning also works. Under the DoD's highly structured planning and budgeting system, American armed forces have been equipped with the finest military hardware in the world. Most of the very successful radar systems in tactical aviation and the electronic countermeasures to defeat enemy radar systems are products of the traditional system. But, this impressive military materiel has been developed at great cost and almost everyone acknowledges the traditional development cycle is far too long to support the modern military.

As the IR system examples in this paper demonstrate, chaotic evolutionary development also occurs in DoD and has been responsible for many combat successes. Such development has the demonstrated potential to be cheaper and much more responsive to a changing environment. Currently, however, this type of development is exploited on an ad hoc basis in competition with and sometimes contradictory to the established plan. The development saga of the Sidewinder vividly highlights this distinction. Since we live in a rapidly changing world with uncertain security challenges for the future, it seems obvious that we should shift toward the chaotic evolutionary development model, as many in the business world, faced with the same set of challenges, are currently attempting to do. Under the current budget system, this will be extremely difficult for DoD to accomplish. Within the tactical aircraft community, which this paper has concentrated on, the problem is clear. The next generation of tactical aircraft (the Super Hornet, the F-22 Raptor, and the Joint Strike Fighter) are already planned for the next few decades and they *already* exceed projected development budgets. Under these conditions, there will be few resources, either in funding or effort, available for innovative forms of development.

Recommendations

Making specific recommendations on what future systems to pursue or what organizational system to develop goes against the basic premise of this paper. Since we live in such uncertain times, planning for success is, at best, pointless and might even be counter-productive. The right question, as stated in the introduction, is how to develop a culture and organization that can best take advantage of chaotic evolutionary development. Such development has worked well for nature, is the new paradigm for businesses adjusting to their own fast-paced, uncertain environment, and already exists and is exploited within small segments of DoD, as numerous examples in this paper have shown. But it can be done much better.

First of all, DoD should stop treating "chaotic" development as an aberration. Unplanned or "other than planned" successes should not be considered as "failures" of the system. Especially in this time of "strategic pause," when the risk from failed experimentation is low, evolutionary development should become part of the system. In addition, the chaotic nature of such development should be embraced. Innovation, creativity, and "out-of-the-box" thinking need to be nurtured, not just tolerated. However, shoehorning chaotic evolutionary development into the current budget system where we must plan a six-year budget cycle two years ahead of time will be extremely difficult. The entire DoD planning, programming, and budget system is the first place we should look for experimentation and adaptation.

Fortunately, there is no lack of advice. Business books like *Competing on the Edge* are full of advice on how to structure organizations for a chaotic environment. The original management guru, Tom Peters, even suggests organizations can "thrive on chaos."[11] Advice specific to the military is also available. The book, "Sidewinder," used as a reference for this paper, describes Bill McLean's successful design philosophy and the author's own interpretation of what *made* China Lake such a creative organization (the use of past tense represents the view of the "Sidewinder" author).[12] The Joint Forces Quarterly, Autumn/Winter 1998-99, spurred by the recent creation of Joint Forces Command as the center for joint experimentation, contains a thoughtful article on DoD use of experimentation as a way to prepare for an uncertain future.[13] The article questions whether Joint Forces Command can truly be a venue for innovative experimentation since it will be distracted by its still existing geographic "CINC" responsibilities and the potential future responsibilities of "homeland defense" but mostly because it will rely so heavily on the Services for funding and manpower.[14] However, in the spirit of this paper, the establishment of a high profile center for experimentation should be seen as an evolutionary step forward that needs to be vigorously pursued with an open mind on how it will eventually adapt to its role in the DoD environment.

Articles in professional journals and Service School research projects also address the topic of changes in the development system to adapt to uncertain times. Colonel (R) John Warden, architect of the DESERT STORM airwar plan, wrote such an article in the Fall 1999 issue of Airpower Journal. The article recognizes the problems of high cost, long development times, and an unknown threat in an uncertain future. Warden specifically says his suggested approach is "not an evolutionary approach."[15] However, he is undoubtedly referring to the gradual improvement definition, rejected in the introduction of this paper. His suggestion is to build a force with small numbers of many platforms with varied capabilities so the US will define the future, rather than adapting to it.[16] However, such a force would also fit perfectly into the concept of developing an organization/capability whose "success is measured by the ability to survive, to change, and ultimately to reinvent the firm constantly over time," as espoused in *Competing on the Edge*.[17] In other words, Warden's "New American Security Force" is perfectly in tune with the concept of chaotic evolutionary development. The Naval War College thesis of Colonel Dan McCrory specifically applies the chaotic evolutionary analogy to the DoD acquisition process. Colonel McCrory is currently trying to implement these ideas as a program manager at DARPA.[18]

Special Operations Forces (SOF) may provide a useful example for conventional forces trying to embrace chaotic evolutionary development. By definition, SOF are small and have specialized roles so it is tough to draw general conclusions from their activities. However, SOF have embraced IR systems much more fully than conventional aviators and it appears they have done an excellent job of taking advantage of chaotic evolutionary development. Evolution by merger is a constant theme in SOF -- the merging of a cargo aircraft, IR sensors, and Army artillery produced the SOF fixed-wing Gunships. The ability to react quickly to unfilled military niches is also a characteristic of SOF -- the Gunships were developed quickly as a counter to the low tech transportation methods of the Vietnamese that were not vulnerable to the conventional attack methods of the USAF. SOF has also demonstrated the ability to shed vestigial components -- the 20mm cannon, still a planned feature for the F-22, came off the Gunships in the 1990's as the IR threat changed the operational environment. And quick adaptation of new technologies has been an enduring trait of SOF -- SOF aviators have been flying using NVGs for decades while conventional aviators are only recently embracing the concept.[19] While by no means a perfect model of development, procurement, or employment, SOF should be an excellent source of lessons learned for incorporating chaotic evolutionary development more formally into the DoD acquisition process.[20]

One final point needs to be addressed when considering the implications of chaotic, evolutionary development. This paper has focused on the development of systems and technologies and can be rightly criticized for focusing on materiel issues in lieu of organizational and doctrinal issues which many claim to be the other two legs of the triad needed for a real "revolution in military affairs." While the paper is guilty of the materiel bias prevalent throughout DoD, it is important to note that the business community claims the concept of chaotic evolutionary development can be applied to organization and methodology (i.e. doctrine) just as readily as it can be to systems development.[21] Therefore, any criticism based on materiel bias should be confined to the paper and not the overall concept of applying chaotic, evolutionary development to the future of DoD.

Epilogue: Applying the Evolution Analogy to the RMA

A large portion of the DoD modernization program is focused on implementing an information-based Revolution in Military Affairs (RMA). In the National Security Strategy - Year 2000, in the section entitled *Preparing for an Uncertain Future*, the strategy states: "Exploiting the revolution in military affairs is fundamental if U.S. forces are to retain their dominance in an uncertain world." Two sentences later, it states this will be done by "a carefully planned and focused modernization program."[22] Therefore, even though the concept of a "planned revolution" seems to be an oxymoron on the same scale as "jumbo shrimp," it seems the DoD preference for planned development will guide the RMA. Even if this is the case, some lessons from examining the chaotic development of IR systems for tactical aviation can be applied to the oft-predicted revolution.

First of all, chaotic evolution works – a planned revolution is not necessary. "In the box" thinking of constant experimentation and improvement can result in revolutionary improvements in capability, revolutionary changes in the environment, and revolutionary changes in the roles of some systems.

Second, chaotic evolutionary "revolutions" may be hard to recognize. The USAF is still struggling with the implications of the new mode of medium altitude, beyond-visual-range air warfare that was first apparent (in hindsight) over the Bekka Valley almost 20 years ago. This mode of air warfare is highly dependent on command, control, communications, computers and intelligence (C4I), perhaps even more so than on missiles, aircraft, and pilots. The info-based RMA may already be here for tactical aviation!

Another point to consider is that chaotic evolutionary development happens and is not predictable. Unplanned or other than planned successes will undoubtedly occur that will affect the RMA train's route and schedule, possibly even derailing it. DoD needs to continue to experiment, ensure "survival of the fittest," and adapt its planned revolution as necessary. The key should be to manage, not avoid, chaotic development.

As the RMA evolves, system developers should beware of vestigial components. The US Army's attempt to digitize the individual soldier has reached an unfortunate, and somewhat embarrassing, point where so much digital equipment has been piled onto the existing load of a soldier that if he falls, he might experience the "turtle on its shell" phenomenon.[23] If the RMA will make our military forces more capable, what has to go to make it practical (in terms of funding as well as load)? The most critical vestigial question the RMA will have to face is already on the horizon: At what point does the human in a combat platform become the equivalent of tonsils, still performing some useful functions, but not worth the risk?

A very important consideration for an info-based RMA is that evolution based on technology has no natural end. The seemingly endless upgrade of Windows software and Intel hardware that corporate America and non-operational DoD components undergo for relatively minor improvements in staff capability should be a red flag when considering applying the information revolution to warfighting. Nearly all administrative personnel in DoD now have a computer on their desk that is more powerful than that used to design nuclear weapons and advanced aircraft during the height of the Cold War and the next upgrade is already scheduled for the near future. Each successive upgrade that we are given or forced to receive, with its associated de-bugging and re-learning period, takes resources (funds, manpower, and expertise) from what we really require. Is the concept of "good enough" even applicable to info-based systems?

A very clear and applicable lesson from the chaotic development of IR systems is that evolution by merger is a recurring success story. Since an info-based RMA is so highly dependent on high technology in the very specialized fields of software and hardware development, proponents of an info-based RMA should be especially aware of the possibilities of in-breeding and tunnel vision. There is the possibility that the RMA could devolve into information experts designing complex information systems to be part of even more complex information networks in isolation from the non-virtual world. This type of RMA development would almost certainly miss the cross-disciplinary successes and applications that can produce truly revolutionary enhancements to capability.

Another important lesson applicable to the RMA is that losers innovate and competition drives evolution. America is already a conspicuous winner in the military application of information systems. We have no peer competitor and it is often claimed that America is in an arms race with itself. Even our Allies think we are evolving too quickly on the information front.[24] But, that may not be a bad thing. An important lesson from nature is that competition isn't just nice, it's necessary for chaotic evolutionary development. The need for competition may also justify continued inter-Service rivalry. Jointness has done wonders for US warfighting capability and nearly everyone recognizes that more must be done, but a single homogenized purple Service could be a formula for stagnation in the development of new systems. This is an important consideration as information operations migrate to Space Command and an underground revolution brews in the Space community for a separate joint Service.[25]

By far the most important lesson to learn for the developers of an info-based RMA is that technology evolution is easier for the second and successive developers. This is especially true for information systems because of the rise of the internet and globalization. The corollary in the previous section about civilian technology ascendancy in cutting edge IR systems is even more applicable to information systems. As the world's leading info-based society, there is no turning back, or even slowing down, the information revolution in our society and military. However, we must not lose sight of the fact that our dependence on information systems also makes our economy and military most vulnerable to new forms of warfare. Information warfare may be enabled by civilian developers and could be employed on a funding and time schedule that is entirely inconsistent with the DoD development system. This is a truly vital national security issue that is the other edge of the sword we will be wielding after the arrival of the RMA.[26]

Notes

[1] Gould, p. 179. Charles Darwin would probably be shocked at the current chaotic model of evolutionary development.

[2] Gleick, p. 8: "The notion that a butterfly stirring the air today in Peking can transform storm systems next month in New York."

[3] Brown, p.194

[4] Westrum, p.206

[5] WSJ: Dec 31,1999, pg. A12. In the last 5 years, defense R&D has declined slightly (inflation adjusted) while non-defense R&D has increased by 12%.

[6] Personal experience: apocryphal SOCOM story.

[7] IR missiles are already dangerous but their seeker heads have lagged in their evolution. IR sensors have already incorporated many features that could make IR missiles even more threatening. Marginally more threatening dual-band seeker heads are already being offered as low-tech retrofit kits for older Strella's, but true multi-band seeker heads could be developed that would be very difficult to spoof. The CCD imagery

Notes

that is the latest in cheap sensor technology could easily be applied to missiles, again reducing their vulnerability to countermeasures. Most threatening, the marriage of cheap multi-sensor seekers and cheap microprocessor power could lead to truly revolutionary advances in IR missile lethality.

[8] Gould, p. 24.

[9] Personal experience: Advocates of night vision goggles have pushed the "requirement" for night vision "as good as day vision" – an unrealistic goal that saps resources.

[10] Brown, p. 14.

[11] Peters, p. xii.

[12] Westrum, p.168, Chapter 13

[13] Johnstone, p. 15.

[14] Ibid., p. 21. The JFCOM CINC voiced the same concerns while addressing AWC.

[15] Warden, p. 76

[16] Ibid.,. p. 90

[17] Brown, p. 4.

[18] McCrory, pg. iii. The paper argues that a complex, adaptive system, such as DoD acquisition, naturally evolves towards the "edge of chaos" if it follows a few simple rules. Such a system emphasizes searching for the right job rather than doing the current job right – exactly the type of system recommended in *Competing on the Edge.*

[19] Personal experience – Tactical aviators are now planning to use NVGs, as evidenced by latest NVG requirements document which specifies "ejection-compatible" for the first time.

[20] Personal experience: Five years at AFSOC HQ and SOCOM HQ.

[21] Brown, p. 243.

[22] National Security Strategy 2000, pg. 21

[23] Time: Jan 1 2000, p. 34.

[24] Av Week: May 17, 1999, p. 33. A "retired senior French naval aviator" suggested the US should slow its drive for new digital battlefield enhancements to be more in line with its European allies in order to sustain cohesion of the transatlantic alliance.

[25] Personal experience: You don't have to dig very deep to sense the underground revolution among Space personnel for a separate Service.

[26] WSJ, 10 February 2000, p. B6.

Appendix A: E&M Spectrum and Infrared Radiation

The electromagnetic spectrum is just an arrangement of electromagnetic radiation by wavelength or frequency. All electromagnetic radiation follows similar laws of reflection, refraction, diffraction, and polarization and the velocity for all electromagnetic radiation is the speed of light. However, different portions of the electromagnetic spectrum interact with matter in different ways so they are grouped for convenience into different sections such as radar, radio, microwave, infrared, visible, ultraviolet, x-ray, etc. The figure below shows the wavelengths (frequencies) commonly associated with the electromagnetic spectrum with the infrared and visible portion of the spectrum, of primary interest to this paper, expanded for easy reference.

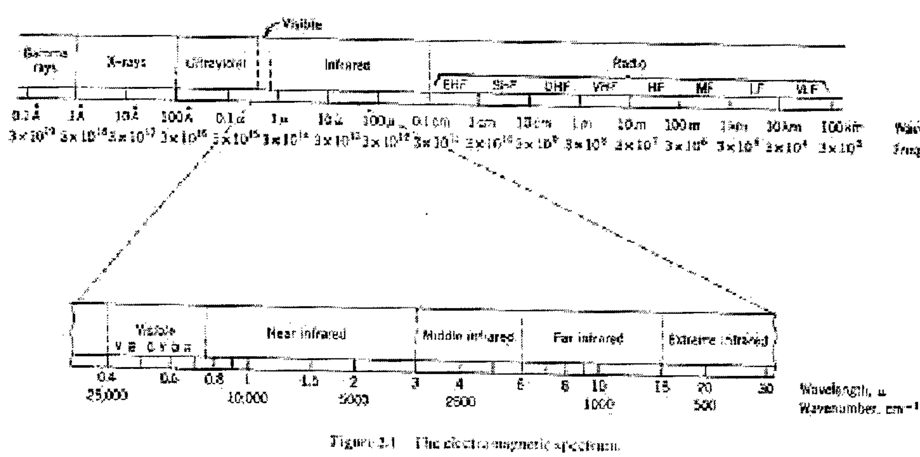

Figure A1: Electromagnetic Spectrum[1]

The reason for infrared "windows" in the atmosphere is that different constituents of the Earth's atmosphere selectively absorb certain wavelengths. The figure below shows the relative transmission through the atmosphere of different infrared wavelengths. The areas of very low transmission (high absorption) are the boundaries between what is commonly referred to as the near (centered on 1 micron), middle (3 – 5 microns), and far (8 –12 microns) infrared regions. These are somewhat artificial distinctions although, at commonly occurring temperatures, the far infrared portion is more dependent on the emissivity of an object (internal source) while the near infrared portion depends almost exclusively on an object's reflectivity (external source). This is a relevant distinction when designing infrared equipment for military purposes.

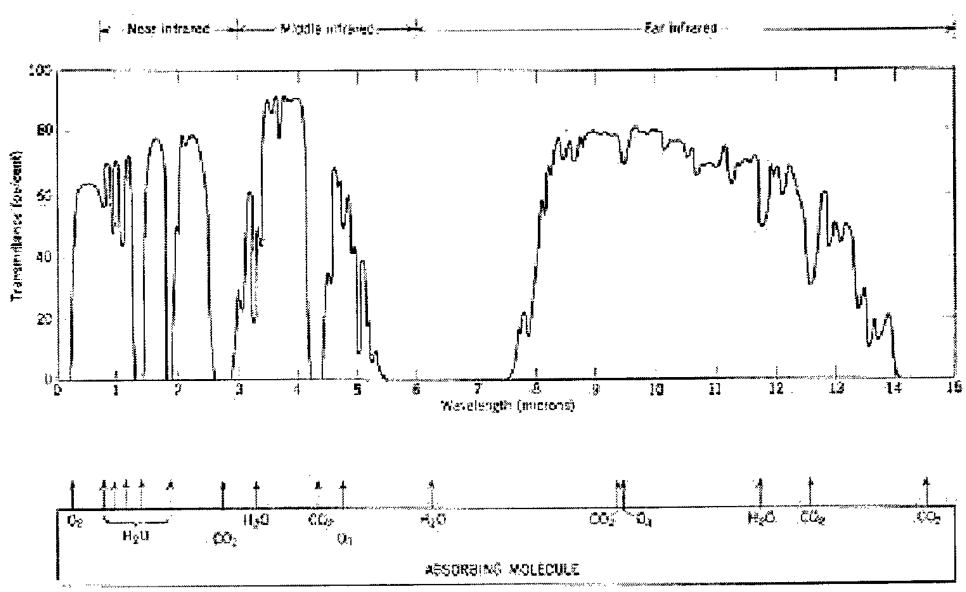

Figure A2: Infrared Windows[2]

Night vision devices (image intensification devices) rely almost exclusively on collecting ambient photons reflected from objects. The figure below shows the relative amounts of infrared radiation available from natural sources at night. Clearly, the moon dominates the night's illumination and the predominance of the illumination is in the infrared region.

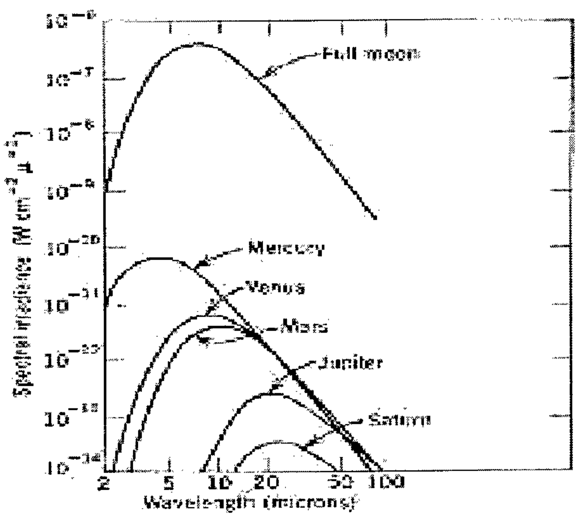

Figure A3: Night Infrared Spectrum[3]

The figure below shows the blackbody curves for the temperature range of 500 degrees K to 900 degrees K, which includes the temperatures for the hot metal tailpipes of turbojet aircraft. The curves display two important characteristics. First, the amount of IR energy emitted (the area under the curve) rises rapidly with temperature. Second, the peak of the curves (maximum emittance) shifts towards shorter wavelengths as the temperature increases. As can be seen, the hot metal of turbojet engines is most "visible" to IR seekers in the near and mid-IR regions.

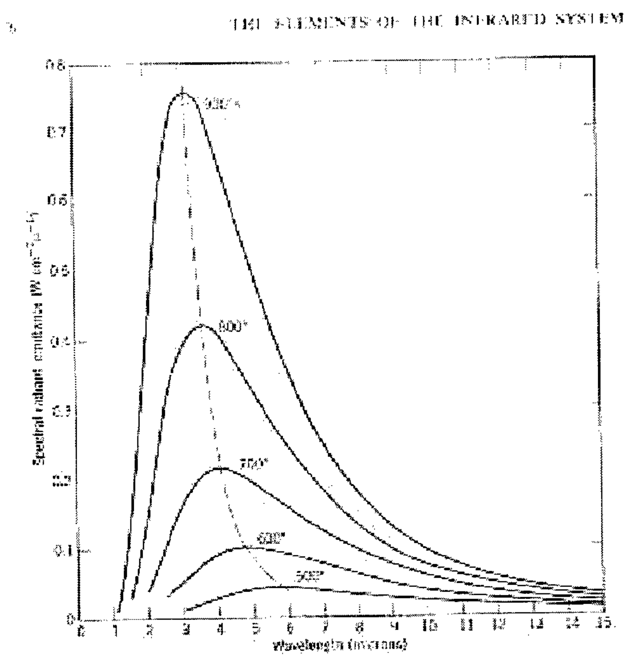

Figure A4: Blackbody Radiation[4]

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[1] Hudson, p. 21.
[2] Ibid., p. 115.
[3] Ibid., p. 104.
[4] Ibid., p. 36.

Appendix B: IR Technical Evolution

Since IR systems were driven primarily by "tech push" and not by formal requirements, it is important to understand how the technology evolved. Infrared systems, like natural evolution, followed a relatively straightforward pattern from simple to more complex systems. Although there were discontinuous breaks in the evolutionary flow, again like natural evolution, the IR systems became better adapted to their environment (night) and more successful as they "evolved." The heart of an infrared system is the detector(s) and detectors' technical evolution drove the overall design of IR systems. The improvements in the detectors can be characterized by the electromagnetic "window" used, the sensitivity, and the cost/complexity. The evolutionary trend has been for detectors to "see" at longer wavelengths, become more sensitive, and drop in cost and complexity.

The Infrared Information and Analysis (IRIA) Center is the authoritative source for infrared technology and systems. Its first publication, the "Handbook of Military Infrared Technology" was published in 1965. It was filled with information on photoconductive materials in the near-IR region and methods for photomultiplication. These two technologies made possible Image Intensification (I2) devices, commonly referred to as night vision devices. These were the first infrared systems used by the military and include devices such as night scopes, first generation night vision goggles, and low light level TV's. These devices had niche military uses for night operations but little impact on tactical aviation.[1]

Image Intensification Technology

Even though the I2 devices are infrared sensors, they are not really heat sensors, the common perception of IR systems. When dealing with I2 devices, it is better to take the term infrared literally – "below red." These devices operate just outside the visible light region around 1 micron wavelength, just below the 0.7 micron wavelength of the color red. For this reason, this E&M window is referred to as near-IR (see figure 2). Image intensification devices work just like a television camera. They gather light energy, photons, and convert them to electrical energy, electrons, that are used to generate a picture on a display. The I2 devices depend on two technologies to function. First, they are sensitive to photons in the near-IR region (i.e. when the detector is hit by near-IR photons, it creates electrons) because these photons are more prevalent than visible photons in a night scene (see App A, figure 3). Even so, there are not enough ambient near-IR photons available at night to generate a picture, so I2 devices also depend on photomultiplication. In photomultiplication, the electrical signal (i.e. number of electrons) generated by the detectors is amplified through a process where the electrons cascade down a tube which generates many electrons each time it is hit by an electron.

One particular application of these early IR sensors did have an effect on tactical aviation. All objects emit IR radiation at all IR wavelengths based on the "blackbody curve." Blackbodies radiate based on a bell-shaped curve centered on a wavelength dependent on their temperature (see App A, figure 3). Hotter objects emit their peak radiation at shorter wavelengths. Only *very* hot objects radiate much energy in the near-IR region. That is why image intensification devices depend on ambient light. The hot metal parts of jet engines, however, *can* be seen by near-IR detectors because of their emitted radiation. This realization set the stage for IR-guided missiles that would home in on the tailpipes of target aircraft.

In 1979, IRIA published "The Infrared Handbook." A shift away from primarily military uses for IR can be inferred from the elimination of the term "military" in the title of the handbook. The earlier handbook had become obsolete because "new detectors had been invented, new materials discovered, and many instrumentation techniques had undergone vast improvement since 1965."[2] The new detectors were, in general, more sensitive (i.e. could operate with less ambient light) and more reliable. The big change, however, was in the materials. Engineers now had photoconductive materials available in the second IR window of the E&M spectrum. This window is from 3-5 microns and is called the mid-IR region (see App A, figure 2). Not only did this allow IR systems to "gather" more photons, it also allowed them to truly exploit the heat-sensing feature of IR radiation. This was because mid-IR detectors could now "see" the IR radiation of objects much cooler than the hot metal of jet engines. Objects such as the internal combustion engines that power modern armies, the exhaust plumes from turbine (i.e. jet) engines, and even the hot spots on fast moving aircraft due to skin friction could now be seen even in the absence of ambient light. This greatly expanded the potential military uses of IR systems.

The third improvement of "improved instrumentation techniques" also had a big effect on the military use of IR systems. The technique of "scanning line arrays" allowed a relatively small group of detectors to fill in a large picture. This was critical because the detectors were still expensive and difficult to maintain. Some even required cryogenic cooling to keep noise levels at a reasonable value.[3] Just as the first IR Handbook was filled with techniques for photomultiplication, the new handbook was filled with clever scanning techniques. These scanning techniques allowed high resolution imaging systems to be packaged in relatively small and reliable packages. This improvement in IR technology had paved the way for an explosion of uses within and outside the military. Tactical aviation was affected by the introduction of Forward-Looking Infrared (FLIR) systems for night flying and very effective IR-guided missiles.

In 1993, the IR Handbook was replaced because of another round of new technological developments. The proliferation of uses for IR systems and new information required an eight-volume publication in lieu of one large handbook. The third window into the infrared was now open thanks to photoconductive materials that were sensitive in the 8-12 micron region, called far-IR. These "bolometers" were true heat detectors allowing "thermal imaging" with no need for ambient light. Two separate advancements made the cost of a detector array plummet. The computer revolution had made the "chips" used to populate an array much less expensive. These chips, called "charge coupled devices (CCD)" made IR systems nearly as simple as a television system. Clever, but complex and expensive, scanning systems were no longer required since it was now cost-effective to simply fill up the entire two-dimensional detector array. In addition, "uncooled" detectors became common, eliminating the need for unreliable and costly cryogenic systems. IR systems could now be made small and reliable enough to fit onto nearly any platform, including retrofitted pods and turrets and even expendable weapons. The term "multi-spectral," meaning systems could be developed to take advantage of the different qualities of each IR window, became routine.

The advent of cheap IR systems has made IR systems feasible for the civilian consumer. In a turnaround from the early days of IR systems, when military uses predominated, the civilian development community has embraced the current state of IR technology. Night vision goggles are for sale at Sharper Image stores. Digital camcorders now use CCD technology and at least one such camcorder has extended its spectral range into the infrared, causing a much-overhyped sensation about the ability to "see" through clothing. The 2000 model of the Cadillac STS will offer a "heads up display" on the dashboard that will display a thermal image to help drivers see through smoke, haze, and at night.[4] Given the vitality and resources of civilian development efforts, this move into a formerly military technology could have broad implications for the future of IR systems development and perhaps military systems development in general (discussed in the summary of the paper).

Notes

[1] Personal experience – Special Operations aviators have flown using night vision goggles (NVG) for decades. Tactical aviators are just now starting to use them.

[2] IR Handbook, pg. v.

[3] Hudson, p.373.

[4] WSJ, 28 January 2000, p. W13C. Drivers in areas where deer are a hazard should find this option particularly useful since warm-blooded mammals show up very well on thermal imagers.

APPENDIX C: Radar Limitations

The first difference is the **wavelength** used. Long wavelengths mean radar is inherently low resolution. Resolution is fundamentally determined by the wavelength used and radar wavelengths are millions of times larger than visible wavelengths. For instance, the WWII bombers were only able to "see" things such as major river bends and large industrial areas. Receiver size is also determined by wavelength; the eyeball has to be replaced with large antennae.

A second major difference is that eyeballs are passive systems, receiving reflected energy from another source, while radar systems are **active**, receiving energy that they must transmit. While this gives radar "independence" in its use (i.e. visual systems [eyes] cannot see if there is no source), it is also a problem. First of all, it creates serious power concerns. Light and radar (in fact, all electromagnetic waves) fall off in power by a factor of range squared (R^2). That is to say, if an object moves 5x further away, the E&M energy reaching the object falls off by a factor of 25 (5 squared). Since radar must travel to a target *and* return, radar range falls off by a factor of R^4 (R^2 twice). So, if a radar target is 5x further away, the E&M energy returned to the radar falls off by a factor of 625 (5 to the fourth). This R^4 reduction forces radar system to be relatively powerful, with resultant weight, size, and complexity issues. A secondary complexity issue is that transmit/receive systems are inherently more complex (therefore less reliable and maintainable) than receive only systems. A third problem with an active system is "emissions control" (EMCON). Visual systems *can* use a searchlight when natural sources are not available at the risk of highlighting their position. Radar's *must* use a "searchlight" in their portion of the spectrum and, therefore, always run the risk of highlighting their position to an adversary.

A third major difference with radar is that it is **non-intuitive**. A raw radar return resembles the well-known Rohrshach inkblot test. Early radar pioneers described the task of interpreting radar returns as the science of "blobology."[1] A radar signal must be processed to transform the radar return into an image the human brain can readily interpret. Even after processing, it requires a well-trained operator to extract useful information from a radar "picture" (although the tremendous increase in processing power we have experienced in the last decade has taken some of the burden off the operator). Another non-intuitive aspect of radar is that its "vision" is based on the reflectivity of a target, a physical property that does not necessarily coincide with the object's color or size, the primary visual cues. The dispersion of a radar beam is also non-intuitive. "Line-of-sight" no longer applies. And, quite unlike vision, radar can be "looking" in several different directions at once, due to sidelobes.

These major differences between radar and visual systems all create problems in themselves for the designers of tactical radar systems. Taken together, they create the conditions for the primary tactical problem with radar systems. Because they must transmit, at a non-natural frequency, at relatively high power, with wide dispersion, and must be processed, radar signals are susceptible to **countermeasures**. The field of ECM (electronic counter-measures) followed close on the heels of the military exploitation of radar. Jamming, spoofing, chaff, and other now-common ECM tools were all used in WWII. In fact, the countermeasure contest between the German air defense and the RAF night bombers got so intense and frenetic during the war that both sides were using ECCM (electronic counter-counter measures) by the end of the war.[2]

To be fair, radar systems have some advantages over visual systems. One advantage of radar is inherent in its name. Radar is such a commonly used term, that it is easy to forget it is really an acronym, standing for Radio Detection and **Ranging**. Because it transmits and receives, radar can determine the range to an object it "sees." Another phenomenon of a transmit/receive system is that it can exploit the **Doppler** effect, whereby the frequency of an E&M wave gets shifted when reflecting off a moving object. While this complicates the basic radar concept, engineers clearly made lemonade out of this lemon by using the Doppler shift to determine the speed of targets and to eliminate ground clutter (since the ground does not move), along with other militarily useful applications. The non-line-of sight feature of radar can also be exploited in some circumstances (e.g. radar can "see" behind terrain and "over-the-horizon" in some circumstances).

Notes

[1] AWC speaker: academic year 2000.

[2] Not surprisingly, British authors cover this area well. Keegan's *The Second World War*, p. 429 has a very concise summary of ECCM events. For a detailed discussion of WWII ECM/ECCM, see Ken Delve's *Nightfighter: the Battle for the Night Skies*.

Appendix D: Millimeter Wave Applications

Very short wavelength radar

One way to think of millimeter waves is as very short wavelength radar. The short wavelengths offer relatively high resolution, narrow beam divergence, and small antenna size, thereby offsetting some of the traditional limitations of radar. This is a straightforward approach to MMW and is already in prototype stage for many systems. An improved Apache attack helicopter fire control system uses MMW radar, many MMW seeker heads for weapon terminal guidance have been proposed, and it is the leading candidate for use by the Autonomous Landing Guidance (ALG) system. The ALG is an attempt to put a landing aid system onboard aircraft that allows inclement weather landings with no, or minimal, on-site landing aids. This concept has great military and civilian aircraft potential, allowing landings at unimproved (or uncooperative) airfields that could previously only be done if large and expensive precision approach equipment was available and certified. In recognition of this potential, it has been partially funded by DARPA under their Technology Reinvestment Program for dual-use technologies.[1]

The basic concept for ALG is to use GPS guidance to get close to the airfield (on final approach) and then use the MMW radar to "see" through the weather, allowing the pilot to complete the approach and land using standard visual techniques. Since the MMW radar only requires the range to complete the final approach to the airfield (3 - 4 miles), it can be a very low power system, minimizing system size and the potential problem of interference if multiple aircraft are approaching the airfield. It also minimizes the military-unique problem of highlighting aircraft operations to enemy detectors.

MMW appears to be a radar solution well suited for the specific, yet critical, mission of landing at forward, unimproved airfields in inclement weather.

Very long wavelength infrared (PMMW camera)

Another way to look at MMW is to consider it to be very long wavelength infrared radiation. This is a very non-traditional approach to MMW use, as is obvious by the fact that engineers talk about MMW in frequency terms (GHz) like a radar, and not in terms of wavelength, as in IR systems. A typical blackbody radiation curve will show MMW radiation at 94 GHz to drop off by a factor of six from what is traditionally considered the infrared spectrum centered around the 3 - 5 micron wavelength region. However, it is important to understand that the typical curves displayed are on a logarithmic scale so the amount of radiation is dropping off by a factor of ten to the sixth power. This means the power of MMW radiation from a hot object is typically one millionth that of the IR energy emitted. Until recently, that very weak signal has been ignored. Several factors have now made it possible to exploit such a low power signal for sensing purposes. First of all, detectors have gotten incredibly sensitive and can actually respond to such a weak signal. Second, there is very little natural background noise at 94 GHz while there is a lot of background noise in the typical IR spectrum. Therefore, while the signal is very weak, the signal-to-noise ratio, the quantity that really matters, is not that bad. Third, digital signal processing has made enormous strides in the last decade and has made it possible to extract information from very weak signals.

Another candidate for the ALG system is attempting to develop a MMW sensor that is very IR-like, based on these technology advances. The Passive Millimeter Wave Camera looks like and produces imagery like a crude FLIR. It has a lens and a focal plane array with a set of detectors that are sensitive to MMW radiation. The primary drawback of the system is that the long wavelength of MMW radiation necessitates a large lens aperture and therefore, a large overall system size.[2]

While the MMW camera concept may not be practical as a landing aid because of its size, it is worth investigating further because of a unique phenomenon associated with MMW radiation that gives it real potential for tactical aviation as a passive IR-like sensor. This phenomenon is the radar-like quality of reflecting very well from metal objects. If you look down on a metal object, as from an aircraft, metal objects will reflect the MMW signature of the very cold (as compared to the ground) sky. So, whereas IR systems could detect tanks in the desert during Desert Storm because the tanks were warmer than the sand, a MMW detector would be able to detect tanks in the desert because they appeared to be very cold. Most interestingly, MMW radiation has radar-like penetration characteristics so it has the potential to do the much tougher job of detecting tanks under trees (important enough after the Kosovo campaign to warrant its own military acronym – TUT).

MMW radiation also has decent weather penetration characteristics, potentially allowing an "all-weather" passive IR system, another very useful military sensing application. For instance, combat search-and-rescue could immediately benefit from such a system. Aircrews already carry a blanket in their survival gear that is camouflaged on one side and "silvered" on the other, depending on whether you are trying to hide or to be seen while staying warm. The "silvered" side is highly reflective in the MMW region. Therefore, in a night rescue (the standard these days), the silvered side would not be visible in the dark but it would act as a large, *non-emitting* radar beacon to an aircraft equipped with a passive MMW sensor. The concept of a passive beacon is very important. A combat rescue mission is often a race between enemy ground forces and the rescue aircraft. In any rescue situation, the assumption must be made that the enemy will "home in" on any radar/radio emissions and will be actively searching for visual and or IR markers/beacons (which would not be visible in bad weather so are only marginally useful). An all-weather passive beacon that can only be seen by aircraft (because of the need for the sky MMW reflection) equipped with a MMW sensor (too high tech for most adversaries, at least for awhile) would be a great combat rescue tool. And, aircrews already carry it![3]

Hybrid MMW System

An approach which uses a hybrid system to scan in one direction like a radar antenna while scanning in the second dimension like a standard IR focal plane array is much riskier but potentially the most useful system. The MMW array can be laid out like a conformal antenna on the outside of an aircraft's fuselage or wings to allow a large aperture (for high resolution) without the big, boxy shape of the MMW camera concept. A MMW array on the underside of a Predator's wings would allow the UAV to "see" through a cloud deck without emitting. Staying above a cloud deck would render it safe from IR missiles and visually or electro-optically aimed AAA. For the same reason, a conformal MMW antenna on the side of an AC-130 Gunship would have potentially revolutionary effects on that weapon system's mission. The hybrid concept and both the applications mentioned above have already been proposed.[4]

Notes

[1] Lear Astronics brief: POC = James I. Granger, B.G. USAF (RET.)

Notes

[2] TRW brief: POC = Gerald J. (Jerry) Stiles, Ph. D. jerry.stiles@trw.com
[3] Ibid.
[4] Thermotrex brief: POC = Matthew R. Kambrod (consultant); John Lovberg

Bibliography

Accetta, Joseph S., and Shumaker, David L., Executive Editors, *Infrared & Electro-Optical Systems Handbook*, Infrared Information and Analysis Center, Environmental Research Institute of Michigan and SPIE Optical Engineering Press, Washington and Michigan, USA, 1993.

Air War College, Academic Year 2000 (AWC Y2K): Unpublished academic notes and lectures.

Ajami, Fouad, *Mr. Bin-Laden's Neighborhood*, US News & World Report, pg. 26, September 7, 1998.

Almond, Denise L., Desert Score: U.S. Gulf War Weapons, Carroll Publishing Company and United Communications Group – Periscope in cooperation with the U.S. Naval Institute, 1991.

Barker, Ralph, *The RAF at War*, Time-Life Books, Alexandria, VA, 1981.

Brown, Shona L. and Eisenhardt, Kathlen M., *Competing on the Edge: Strategy as Structured Chaos*, Harvard Business School Press, Boston, MS, 1998.

Clarke, Patrick E., *Litening Strikes*, Citizen Airman, Vol. 51 Issue 1, pp. 12-13, February 1999.

Cohen, Eliot A., *Gulf War Air Power Survey, Vol. 5: A Statistical Compendium and Chronology*, Washington, D.C., 1993.

Coonts, Stephen, *Flight of the Intruder*, Naval Institute Press, Annapolis, MD, 1986.

Cordesman and Wagner, *The Lessons of Modern War, Volume I: The Arab-Israeli Wars 1973 - 1989,* Westview Press, Boulder and San Francisco, 1990.

Cordesman and Wagner, *The Lessons of Modern War, Volume III: The Afghan and Falklands Conflicts,* Westview Press, Boulder and San Francisco, 1990.

Delve, Ken, *Nightfighter: The Battle for the Night Skies*, Arms & Armour Press, London. US distribution = Sterling Publishing Co. Inc., NY, NY, 1995.

Gleick, James, *Chaos: Making a New Science*, Penguin Books, NY, NY, 1987.

Gordon, Michael R. and Trainor, General Bernard E., *The General's War*, Little, Brown, and Company, Boston, 1995.

Gould, Stephen Jay, *The Panda's Thumb,* W.W. Norton & Co., NY, NY, 1980.

Grant, Rebecca, *The Radar Game*, IRIS Independent Research, Arlington, VA, 1998.

Gunston, Bill, *Guide to the World's Airborne Missiles,* Salamander Books, Ltd., London UK, 1993.

Gunston, Bill and Spick, Mike, *Modern Air Combat,* Crescent Books, NY, NY, 1983.

Hallion, Dr. Richard P., SES USAF, *Control of the Air: The Enduring Requirement,* Bolling Air Force Base: Air Force Museums and History Program, 1999.

Hudson, Richard D., Jr., *Infrared System Engineering,* John Wiley & Sons, NY, NY, 1969.

Johnstone, Mark A., Ferrando, Stephen A., and Critchlow, Robert W., *Joint Experimentation: a Necessity for Future War,* Joint Forces Quarterly, pp. 15-24, Autumn/Winter 1998-99.

Joint Vision 2010, Chairman of the Joint Chiefs of Staff, 1996.

Keaney, Thomas A. and Cohen, Eliot A. *Gulf War Air Power Survey Summary Report.* Maxwell AFB, AL: Air University Press, Academic Year 2000.

Keegan, John, *The Second World War,* Viking Penguin, NY, NY, 1990.

Miller, Edward S., *War Plan Orange,* Naval Institute Press, Annapolis, MD 1991.

Murray, Williamson, *Air War in the Persian Gulf,* The Nautical & Aviation Publishing Company of America, Inc., Baltimore, MD, 1990.

New World Vistas: Air and Space Power for the 21st Century: Attack Volume, USAF Scientific Advisory Board, 1995.

Peters, Thomas J., *Thriving on Chaos: Handbook for a Management Revolution*, Alfred A. Knopf, NY, NY, 1987.

Spector, Ronald H., *Eagle Against the Sun,* Vintage Books, NY, NY 1985.

Thompson, Mark, *The Army's Futuristic Mutant Snafu Turtles*, Time, pg. 34, Jan 1 2000.

Tirpak, John A., *Brilliant Weapons,* Air Force Magazine, pp. 48-53, February 1998.

Westrum, Ron, *Sidewinder: Creative Missile Development at China Lake,* Naval Institute Press, Annapolis, MD, 1999.

Aviation Week & Space Technology (Av Week):

AMRAAM Meets Funding…, pp. 25-26, 4 November 1985.

Dornheim, Michael A., *US Intensifies Efforts to Meet Missile Threat*, pp. 36-38, 16 October 1995.

Fulghum, David A., *Improved Missiles Trigger Jammer Need*, pp. 32-33, 27 September 1999.

Fulghum, David A., *Kosovo Conflict Spurred New Airborne Technology Use*, pp. 30-31, 23 August, 1999.

Fulghum, David A., *Security Leaks and the Unknown Bedeviled Kosovo Commanders*, pp. 33-34, 1 November 1999.

Fulghum, David A., *Weapons, Intelligence Targeted in Probe*, pp. 69-71, 26 July 1999.

Fulghum, David A., *Yugoslavia Successfully Attacked by Computers*, pp. 31-32, 23 August 1999.

Hughes, David, *Luftwaffe MiG Pilots Effective with Archer*, pg. 39, 16 October 1995.

Kandelo, Stanley W., *F-22 Will Set Standard for Next-Century Fighter*, pp. 46-48, 3 August 1998.

Mann, Paul, *Kosovo Lessons Called Ambiguous*, pp. 32-36, 28 June 1999.

Morrocco, John D., *F-117A Fighter Used in Combat for First Time in Panama*, pp. 32-33, 1 January 1990.

Morrocco, John D., *Kosovo Conflict Highlights Limits of Airpower and Capability Gaps*, pp. 31-33, 17 May 1999.

Morrocco, John D., *New ASOCs Link Regional Airspace*, pp. 57-58, 22 March 1999.

Scott, William B., *Bad Weather No Deterrent for New Long-Range Weapons*, pp. 66-67, 3 May 1999.

Scott, William B., *LANTIRN Gives Tomcat Night Attack Role*, pp. 40-43, 10 June 1996.

Wall, Robert, *SEAD Concerns Raised in Kosovo*, pg. 75, 26 July 1999.
USAF Generals Concur on B-1 Bomber Upgrade, pg. 70, 5 October 1992.

Wall Street Journal (WSJ):

Clinton Plans Major Initiative on Scientific Research, pg. A12, 31 December 1999.
KPMG Evolution Advertisement, pg. A15, 5 January 2000.
A Sedan With a Secret Weapon, pg. W13C, 28 January 2000.
Internet is Arena for Activism, Terrorism, pg. B1/6, 10 February 2000.